Deep-Sea Research Part II 135 (2017) 1–6

Contents lists available at ScienceDirect

Deep–Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Introduction

Arctic Ecosystem Integrated Survey (Arctic Eis): Marine ecosystem dynamics in the rapidly changing Pacific Arctic Gateway

ARTICLE INFO

Keywords:
Arctic
Northern Bering Sea
Chukchi Sea
Fish
Zooplankton

1. Introduction

Arctic Marine Ecosystems are undergoing rapid changes associated with ice loss and surface warming resulting from human activities (IPCC, 2013). The most dramatic changes include an earlier ice retreat and a longer ice-free season, particularly on Arctic inflow shelves such as the Barents Sea in the Atlantic Arctic and the northern Bering Sea and Chukchi Sea in the Pacific Arctic, the two major gateways into the Arctic (Danielson et al., 2016; Frey et al., 2015; Serreze et al., 2007; Wood et al., 2015). The retreat of Arctic sea ice has opened access to the Arctic marine environment and its resources, particularly during summer, and among other changes has brought with it increased research activities. For the Pacific Arctic region, these activities have led to several recent compendiums examining physical, biogeochemical, and biological patterns and trends in this rapidly changing environment (Arrigo, 2015, 2016; Arrigo et al., 2014; Bluhm et al., 2010; Dunton et al., 2014; Grebmeier and Maslowski, 2014; Hopcroft and Day, 2013; Moore and Stabeno, 2015).

Changes in ice and thermal conditions in the Pacific Arctic impact all components of the ecosystem including benthic infauna and epifauna (Grebmeier et al., 2006a; Nelson et al., 2014), microbes and zooplankton (Ershova et al., 2015; Nelson et al., 2014), as well as fishes, seabirds, and marine mammals that provide important subsistence resources for communities in the Pacific Arctic (Moore et al., 2014). Despite recent advances, significant gaps remain not only in our understanding of these impacts, but also in describing basic life history characteristics of key fish and invertebrate species in the Pacific Arctic, such as Arctic cod (*Boregadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*), which have been identified as potential target species for a fishery (NPFMC, 2009). Other fish species that currently occur in low abundances north of Bering Strait, including salmon (*Oncorhynchus* spp.), yellowfin sole (*Limanda aspera*), Bering flounder (*Hippoglossoides robustus*), and walleye pollock (*Gadus chalcogrammus*), have the potential to expand into the Arctic, with unknown consequences for the ecosystem (Hollowed et al., 2013; Logerwell et al., 2015; Moss et al., 2009; Nielsen et al., 2012).

The Pacific Arctic Gateway, encompassing the broad shelf regions of the northern Bering Sea and Chukchi Sea, has a strong influence on the Arctic Ocean through the transport of freshwater, heat, nutrients and plankton from the Subarctic to the Arctic (Roach et al., 1995). As a transition zone between subarctic and arctic communities, this region is characterized by strong gradients in species composition, diversity, and abundance of fish and invertebrates (Mueter et al., 2013; Stevenson and Lauth, 2012). These strong gradients imply that small shifts in the distribution of water masses and biological assemblages can be associated with large changes at a given location such as a seabird colony or coastal community. Therefore, broad-scale surveys are essential to linking biological assemblages to biophysical gradients in the environment in order to understand the consequences of a changing environment on these assemblages.

2. Arctic Ecosystem Integrated Survey

The Arctic Ecosystem integrated survey (Arctic Eis, https://web.sfos.uaf.edu/wordpress/arcticeis/), supported by the Bureau of Ocean Energy Management (BOEM), the Coastal Impact Assistance Program (CIAP), and the National Oceanic and Atmospheric Administration (NOAA), conducted comprehensive ecosystem surveys over two years (2012 and 2013) on the US portions of the Northern Bering Sea and Chukchi Sea shelves. Recognizing the relative lack of information on fish populations in the region, the primary goals of the project were to (1) collect baseline fisheries and oceanographic data to enable resource managers to better predict effects of climate and human impacts on ocean productivity and on the ecology of marine and anadromous fish species within the northeastern Bering Sea and Chukchi Sea, (2) assess the distribution, relative abundance, diet, energy density, size, and potential predators of juvenile salmon and other commercially or ecologically important marine fishes (e.g. forage fishes) within the region, and (3) evaluate the effect of climate change on the health and status of pelagic fishes within the region.

http://dx.doi.org/10.1016/j.dsr2.2016.11.005

Available online 12 November 2016
0967-0645/

Fig. 1. Grid of sampling stations sampled during the 2012 and 2013 Arctic Eis surveys. Not all stations could be sampled each year due to the presence of sea ice or inclement weather. All paired surface and bottom trawl stations (triangle, inset black circle) occurred in the Chukchi Sea north of Bering Strait. Disparate surface trawl (black circle) and bottom trawl (triangle) sampling did occur. An acoustic survey was conducted along east-west transects between stations throughout the survey region. Midwater trawling (grey square) was conducted to sample aggregations of midwater fishes identified by the acoustic survey. Oceanography stations (black cross) denote stations where no fishing gear was deployed; however, oceanographic sampling (physics, chemistry, plankton) was conducted at all main stations as well as the additional 'Oceanography only' stations in the Chukchi Sea.

Ecosystem surveys focused on assessing biological resources on the seafloor and throughout the water column (zooplankton, fish, invertebrates) and included oceanographic sampling to assess water mass characteristics (temperature, salinity), nutrient concentrations, and phytoplankton biomass. To assess biological resources, surveys used (1) bottom trawls to sample fish and invertebrates on the seafloor, (2) surface trawls to sample fish in the surface layer, including juvenile salmon, forage fish and juvenile life stages of bottom fishes, (3) plankton nets to sample zooplankton and larval fish, and (4) acoustic surveys in combination with mid-water trawls to sample fishes throughout the water column and to assess the abundance and biomass of selected species (Arctic cod; saffron cod; Pacific herring, *Clupea pallasi*; and capelin, *Mallotus villosus*). In addition, seabirds were surveyed along the ship's track to assess their species composition, distribution and abundance throughout the region. Sampling was conducted on an extensive grid of sampling stations (Fig. 1) and along east-west transects (acoustics, seabird observations). Subsamples of fish were returned to the laboratory for analysis, including (1) genetic analyses to determine the population structure of Arctic cod, saffron cod, capelin and salmon across the survey region and throughout the Pacific Arctic, (2) otolith analyses to determine ages and growth rates of Arctic cod, saffron cod and chum salmon (*Oncorhynchus keta*), (3) diet analyses to determine the food habits of selected species, (4) stable isotope analyses to determine the trophic position of, and dietary sources for, selected species, and (5) energetic and hormonal analyses to assess the physiological condition of fishes in the study region.

The contributions assembled here reflect the breadth and diversity of the science conducted as part of the Arctic Eis project and provide a significant step forward in our understanding of the northeastern Bering Sea and Chukchi Sea ecosystems, in particular with respect to ecologically important fish and crab species. A major legacy of the project will be the databases that will be accessible through the Alaska Ocean Observing System's Arctic Portal (http://portal.aoos.org/arctic). In addition to these databases and published studies, a major benefit of the project was that it provided training for several graduate students, five of whom contributed as first authors to this issue. In combination, these contributions mark an important milestone towards improving our capacity to predict the impacts of climate change and variability on marine ecosystems in the Pacific Arctic and throughout the wider Arctic.

3. Major findings

3.1. Advection and winds: Two contrasting years

Oceanographic conditions differed greatly between 2012 and 2013 due to differences in local winds and in the flow of Pacific waters through Bering Strait (Danielson et al., 2016). For example, winds were more persistent from the northeast in 2013 and were associated with flow reversals in the Alaska Coastal Current and with the advection of Arctic waters onto the Chukchi Shelf via Barrow Canyon. These contrasting conditions were associated with differences in nutrient concentrations and abundances of biota in the Chukchi Sea at all trophic levels (Danielson et al., 2016; De Robertis et al., 2016; Pham and Kuletz, 2016; Pinchuk and Eisner, 2016). The influence of Pacific waters in the eastern Chukchi Sea was more limited spatially in 2012, but concentrations of nutrients and chlorophyll *a* (Danielson et al., 2016), the density of zooplankton such as the copepods *Neocalanus* spp. and *Eucalanus bungii* (Pinchuk and Eisner, 2016) and the density of midwater fishes (De Robertis et al., 2016) in waters originating on the Bering Sea shelf were all higher in 2012 compared to 2013. While the reasons for these differences remain uncertain, Danielson et al. (2016) hypothesize that differences in salinity and nutrients may be a consequence of diminishing net transport through Bering Strait from 2011 to 2012. Although a link between the zooplankton community and chlorophyll *a* or nutrients has not been established, moderate to strong coupling between zooplankton, pelagic fish, benthic, and seabird communities (Pham and Kuletz, 2016; Sigler et al., 2016) suggest that differences at the lower trophic levels, whether linked to inflow through Bering Strait or local processes, reverberate throughout the food web.

The intrusion of Arctic waters onto the northeastern part of the shelf in 2013 (Danielson et al., 2016) was most apparent in differences in the zooplankton and fish communities. An Arctic community of zooplankton characterized by *Calanus hyperboreus, Metridia longa*, *Pareuchaeta glacialis,* and *Themisto abyssorum* was much more widespread over the shelf in 2013, while species of Pacific origin were more widespread and more abundant on the shelf in 2012 (Pinchuk and Eisner, 2016). Similar to Arctic zooplankton species, young-of-year Arctic cod were much more widespread and abundant in 2013 compared to 2012 (De Robertis et al., 2016), suggesting an Arctic origin.

The observed differences between 2012 and 2013 are consistent with the observation that in 2012 the distribution of biological communities from plankton through seabirds, including epibenthic fish and invertebrates, largely reflected the distribution of water masses (Sigler et al., 2016). The observed spatial gradients in 2012 are consistent with the response of these communities to hydrographic differences between 2012 and 2013, which imply an expansion of the Arctic community (sensu Sigler et al., 2016) in 2013, reflecting the increased extent of Arctic water masses, and a contraction of the Chirikof Basin / southern Chukchi Sea community, reflecting a reduced extent of Pacific waters on the shelf.

3.2. First comprehensive assessment of midwater-fishes

The Arctic Eis surveys included the first-ever acoustic trawl surveys of the US portions of the northern Bering Sea and Chukchi Sea, providing abundance estimates of pelagic age-0 Arctic cod (*Boreogadus saida*), saffron cod, capelin, and Pacific herring. To estimate abundances, several methodological challenges related to the presence of large numbers of jellyfish and to the small size of fishes had to be overcome. First, large jellyfish in the study region, in particular the scyphomedusa *Chrysaora melanaster*, can dominate biomass in the water column and impede the partitioning of acoustic backscatter among different organisms. The Arctic Eis survey provided ideal conditions to estimate the target strength of C. *melanaster* that was used to improve estimates of target species abundances in mixed-species assemblages (De Robertis and Taylor, 2014). Second, acoustic-trawl surveys require reliable estimates of the size and species composition from midwater trawls in order to convert acoustic backscatter to abundances. However, the mid-water fish assemblage in the Chukchi Sea is dominated by very small juvenile fishes (often < 40 mm), which are inadequately sampled by the trawl sampling gear used for the survey (De Robertis et al., 2016). The authors developed a novel experimental and statistical approach to estimate trawl selectivity for the species of interest to correct abundance estimates for the biases associated with trawl sampling.

Results from the acoustic trawl survey revealed dense aggregations of young-of-year Arctic cod in the Northeast Chukchi Sea in both years (De Robertis et al., 2016). Moreover, results suggest that juvenile gadids and forage fish partition the study region spatially with juvenile Arctic cod dominating in the Northeast Chukchi Sea north of 69.5°N, saffron cod occupying Alaska Coastal Waters of the Chukchi Sea from 66.5 to 69.5°N and Pacific herring distributed largely south of 67°N (De Robertis et al., 2016). These three species can serve as indicators for the three cross-assemblage communities identified by Sigler et al. (2016). In contrast, capelin in both years were distributed throughout much of the study area, but were much more widespread and abundant in 2012.

Although early stages of Arctic cod in the study region have been reported previously (Fechhelm et al., 1984; Kono et al., 2016; Norcross et al., 2009; Wyllie-Echeverria et al., 1997), this is the first documentation of a dense and spatially extensive aggregation of age-0 Arctic cod, extending from Arctic waters (melt water over winter water) into adjacent Pacific water masses. While spawning has been documented to occur under the ice during winter in other regions of the Arctic, the spawning locations that give rise to these dense aggregations are unknown and are the subject of ongoing field and modeling studies funded by the North Pacific Research Board.

3.3. Trophic dynamics of Arctic marine fish communities

Understanding food web interactions is essential to predicting the impacts of climate change, fishing and other anthropogenic impacts on marine ecosystems. For example, it has been hypothesized that shallow continental shelf ecosystems in the Arctic may switch from benthic dominated systems to pelagic dominated systems with potentially profound changes for species composition at all trophic levels (Grebmeier et al., 2006b; Wassmann, 2011). Any changes that affect the pathways of energy from primary producers to upper trophic levels are mediated through trophic interactions; therefore, changes in upper trophic levels can only be predicted if we understand key trophic connections. Earlier studies have described fish food habits of selected fishes in Alaska's Arctic marine ecosystems (e.g. Coyle et al., 1997; Craig, 1984; Cui et al., 2012; Frost and Lowry, 1983) and trophic studies have become a major focus of BOEM's Environmental Studies Program in Alaska (https://www.boem.gov/Alaska-Studies/) in recent years. Four studies in this issue contribute towards a better understanding of trophic dynamics in the region.

Fishes and crab consume a large variety of pelagic and benthic prey in the northern Bering Sea and Chukchi Sea and diets typically differ among species, water masses and with predator size. For example, smaller-mouthed Arctic Staghorn sculpin (*Gymnocanthus tricuspis*) and larger-mouthed shorthorn sculpin (*Myoxocephalus scorpius*), while both generalist feeders that share a similar prey base, partition prey by taxa or size with little apparent overlap in prey use (Gray et al., 2016). However, diets differ spatially and both species have similarly diverse diets with a high proportion of benthic amphipods in the northern Chukchi Sea, possibly reflecting the high benthic productivity in the area (Grebmeier et al., 2006a). Snow crab, a major component of epibenthic biomass across the northern Bering Sea and Chukchi Sea shelf (Bluhm et al., 2009; Kolts et al., 2015), are omnivorous predators in the region, consuming polychaetes, decapod crustaceans (crabs, amphipods), echinoderms (mainly ophiuroids), and mollusks (bivalves, gastropods), with evidence for substantial cannibalism in the Chukchi Sea (Divine et al., 2016).

Stable isotope analyses (Marsh et al., 2016) and multivariate analyses of prey composition across multiple predators (Whitehouse et al., 2016) confirm that trophic levels and diets of most species vary with predator size and among water masses. Except for pelagic forage fishes, most species in the Chukchi Sea rely increasingly on benthic prey as they increase in size (Marsh et al., 2016), reflecting a shift from early pelagic stages to a primarily benthic life style. Hypothesized changes in pelagic-benthic coupling may therefore increase food availability for forage fish, the early pelagic life stages of many fish species and semi-demersal fish that have a more diverse prey base including both pelagic and benthic prey.

Classifying fishes into trophic feeding guilds can simplify the analysis of complex food webs and aid our understanding of climate-related changes to the structure and function of Arctic marine food webs. Whitehouse et al. (2016) identified four feeding guilds in the eastern Chukchi Sea, which reflect the dominant prey types in predator diets: gammarid amphipod consumers, benthic invertebrate generalists, fish and shrimp consumers, and zooplankton consumers. These guilds can form the basis for monitoring and modeling food web dynamics. For example, the hypothesized increase in the flow of energy to the pelagic compartment would be expected to result in improved feeding conditions for zooplankton consumers.

3.4. Winners and losers: Growth and condition in a changing climate

Fish communities in both the Pacific and Atlantic Arctic Gateways are changing. In the Atlantic Arctic, boreal fish species are increasingly replacing Arctic species in the Subarctic-Arctic transition zone (Fossheim et al., 2015; Renaud et al., 2012). Similarly, boreal fishes in the southeastern Bering Sea expand northward during warm periods (Mueter and Litzow, 2008) and there is a potential for at least some species to expand and become established in the Arctic north of Bering Strait or for Arctic species to expand locally (Hollowed et al., 2013). While we cannot yet predict the impacts of a rapidly warming climate on fishes in the Pacific Arctic Gateway with any degree of certainty, results from Arctic Eis support hypotheses that cold-adapted species like Arctic cod may be replaced by competitors that can tolerate a wider range of temperatures, and that some boreal species including salmon may expand northward into the Chukchi Sea.

Arctic cod are a quintessential Arctic species: both juvenile (Laurel et al., 2016) and adult Arctic cod (Helser et al., 2016) are cold-adapted and their growth potential appears to be highest at low temperatures. Arctic cod partially overlap with and have similar diets to saffron cod, walleye pollock, capelin, and other forage fish (e.g. Falardeau et al., 2014; Hop and Gjøsæter, 2013), implying a high potential for interspecific competition. The growth potential of some of these competitors, notably walleye pollock and saffron cod, exceeds that of Arctic cod at temperatures above about 5 °C in the lab (Laurel et al., 2016), suggesting a competitive disadvantage of Arctic cod in warmer waters. Saffron cod collected across the northern Bering Sea and Chukchi Sea during the 2012 Arctic Eis surveys overall attained maximum sizes at a faster rate than Arctic cod (Helser et al., 2016). However, there were regional differences and estimated growth rates of Arctic cod in the Chukchi Sea exceed those of saffron cod in the same year, while saffron cod grew at a faster rate than Arctic cod in the northern Bering Sea. It is unclear to what extent these spatial patterns reflect differences in environmental temperatures or other environmental conditions.

Salmon are an important subsistence and commercial resource in western Alaska and juvenile salmon of all five species of Pacific salmon were collected during the Arctic Eis surveys, although no chinook salmon (*Oncorhynchus tshawytscha*) and only 2 coho salmon (*O. kisutch*) were caught north of Bering Strait. Relatively few juveniles of any salmon species were caught in the Chukchi Sea in either 2012 or 2013, in contrast to the large numbers of pink (*O. gorbuscha*) and chum salmon (*O. keta*) observed during a survey in the southern portion of the Chukchi Sea in 2007 (Eisner et al., 2012), when water temperatures were considerably warmer. These observations suggest the potential for juvenile salmon to expand northward into the Chukchi Sea during warm years to take advantage of feeding opportunities in this productive shelf area and possibly establish new runs in the Arctic (Irvine and Fukuwaka, 2011; Logerwell et al., 2015; Nielsen et al., 2012).

Juvenile chum, pink, and Chinook salmon are widespread and abundant in the northern Bering Sea, largely originating from the Yukon River and Norton Sound (Kondzela et al., 2014). Juvenile salmon utilize the Bering Sea shelf ecosystem during their early marine life to take advantage of high seasonal production (Farley et al., 2009), gaining size and condition as they move offshore (Wechter et al., 2016). Chum salmon in the northern Bering Sea and Chukchi Sea during 2007, 2012 and 2013 entered the ocean environment from mid-June to mid-July and grew at similar rates in both areas and all years based on otolith growth increments (Vega et al., 2016). However, faster growth was observed in the Chukchi Sea in 2013 (Vega et al., 2016) and growth and energy allocation strategies of juvenile pink and chum salmon vary between warm and cold years in the northern Bering Sea (Andrews et al., 2009; Wechter et al., 2016). Both species showed coherent differences in length and condition among years and were longer but had lower energy density in years with warm spring temperatures. While warm spring conditions and larger size is typically associated with enhanced survival of Alaska pink and chum salmon stocks (Mueter et al., 2002), it has been hypothesized that a lack of large, lipid-rich zooplankton prey during warm years could reduce survival for salmon (Farley et al., 2011). However, trends in the abundances of small and large zooplankton differ between the southern and northern portions of the eastern Bering Sea shelf (Eisner et al., 2014); therefore, the consequences of changing thermal conditions for pink and chum salmon survival in the northern Bering Sea remain uncertain.

In contrast to pink and chum salmon, Chinook salmon enter the marine environment at a larger size and the year class strength of Canadian origin Yukon River Chinook salmon appears to be established during the early marine period, prior to sampling during late summer surveys (Murphy et al., 2016). The abundance of juvenile Chinook salmon of Canadian origin on the northeast Bering Sea shelf is highly correlated with adult returns over the last ten years and appears to provide a useful early predictor for future returns. Survival and abundance of juvenile Chinook salmon increased greatly in 2013 and 2014 after more than a decade of very poor survival, raising the possibility of restoring fishing opportunities on the upper Yukon River (Murphy et al., 2016), although the reasons for both recent declines and the apparent recovery remain elusive.

4. Conclusions

Oceanographic conditions differed greatly between 2012 and 2013 due to differences in local winds and in the flow of Pacific waters through Bering Strait (Danielson et al., 2016). The observed differences between 2012 and 2013 are consistent with the observation that in 2012 the distribution of biological communities from plankton through seabirds, including epibenthic fish and invertebrates, largely reflected the distribution of water masses (Sigler et al., 2016). These relationships foretell the effect of climate change on these communities, which will be driven by climate effects on the physical oceanography. In turn, understanding food web interactions (Divine et al., 2016; Marsh et al., 2016; Whitehouse et al., 2016) is essential to predicting the ultimate impacts of climate change, fishing and other anthropogenic impacts on marine ecosystems. Lastly, ocean temperatures and food conditions will influence the community composition for quintessential Arctic (Arctic cod) and subarctic (Pacific salmon) species. The growth potential of some competitors to Arctic cod, in particular walleye pollock and saffron cod, exceeds that of Arctic cod at temperatures above about 5 °C in the lab (Laurel et al., 2016), suggesting a competitive disadvantage of Arctic cod in warmer waters. In contrast, faster growth was observed in the Chukchi Sea in 2013 (Vega et al., 2016) and growth and energy allocation strategies of juvenile pink and chum salmon vary between warm and cold years in the northern Bering Sea (Andrews et al., 2009; Wechter et al., 2016), indicating a competitive advantage for these species in warmer waters (though clouded by the role of climate change on important zooplankton prey species).

Acknowledgements

We thank the captains and crews of the FV Bristol Explorer and FV Alaska Knight, and all the Arctic Eis investigators. Arctic Eis was funded in part with qualified outer continental shelf oil and gas revenues by the Coastal Impact Assistance Program, Fish and Wildlife Service, U.S. Department of the Interior (Contract Agreement Numbers 10-CIAP-010 and F12AF00188), and by the U.S. Department of Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC under Agreement numbers M12AC00009, M12PG00018, and M10PG00050. Arctic Eis is an Ecosystem Studies of the Subarctic and Arctic Seas (ESSAS) endorsed project.

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