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Encl: (1) Final Technical Report for Subject Grant
(2) SF298 for Enclosure

Enclosure (1) is the Final Technical Report for the subject grant along with the (2) SF 298 form. These documents constitute the Final Technical Report and deliverable for ONR Grant# N00014-17-1-2274.

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Arctic Integrated Ecosystem Research Program Final Report

Integrating marine mammal presence into ASGARD: Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments

15 January 2022

K.M. Stafford

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Executive Summary

The ASGARD project

The Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments projects (ASGARD; NPRB awards A91-99a, A91-00a, A94-00, A98-00a) proposed to address known information gaps that hinder a robustly comprehensive application of an ecosystem-based approach to resource management in the U.S. Pacific Arctic region. An ecosystem-based approach is needed to inform and guide policy-driven actions, but this approach requires synthesis of a detailed knowledge base that at the start of the Arctic IERP effort remained incomplete in three important ways. First, existing data were strongly biased to July through October although important ecosystem processes occur in spring, late fall and winter when access is difficult. Second, while we now understand the basic summer regional biogeography (Sigler et al., 2017), net community production (Codispoti et al., 2013), and drivers of species distributions for some taxonomic groups (Feder et al., 1994; Eisner et al. 2013; Blanchard, 2014; Grebmeier et al., 2015a; Ershova et al. 2015), we had scant information from any season about the fundamental chemical and biological rates that mediate carbon cycling and energy flows through the Northern Bering and Chukchi Sea ecosystem. Third, these knowledge gaps curtailed our ability to model the ecosystem, and our ability to make useful projections for management or policy decisions. Passive acoustic monitoring was added to the ASGARD effort to understand the impacts of changing Arctic on marine mammals and to better understand how drivers from physics to plankton to fish to upper trophic level predators are mediated. Thus, this project is not stand-alone but relies heavily on other ASGARD components (ASGARD; NPRB awards A91-99a, A91-00a, A94-00, A98-00a) to function. The present report draws strongly from the Danielson et al. final report as these projects were intimately linked. Herein we include relevant passages from that report but also focus on the passive acoustic data from ASGARD.

Accordingly, the hypotheses developed and addressed by the passive acoustic component of the ASGARD project are:

H-1. *The presence of sub-Arctic marine mammals will be driven by prey availability (fish, zooplankton) that is in turn driven by water mass characteristics*

H-2. *The relationship between ice cover and Arctic species migration from the Bering Sea in to the Pacific Arctic can be quantitatively determined by comparing the onset of acoustic detection with ice advance (or formation) from, and retreat towards, the north (in the winter and spring, respectively).*

H-3. *Temperate marine mammal species will move progressively northwards as seasonal ice cover decreases and remain north of Bering Strait longer.*

H-4. *There will be differences in the species and seasonal occurrence of species between the eastern (eastern SLI and US Bering Strait) and western (Anadyr Strait and Russian Bering Strait) recordings. Data from the A3 climate site and the NE Chukchi Ecosystem Mooring site help establish if there are northern limits to sub-Arctic species and what the southern limits of Arctic species are.*

H-5. *The number of ship passages through both sides of the Bering Strait will continue to increase over time*

Summary of Findings

Select key finds and descriptions of novel sample collections that target the proposed hypotheses and that are presented in the chapters of this report include the following highlights.

- Subarctic baleen whales are recorded in the northern Bering and southern Chukchi Seas from late spring into early winter and at times, overlap temporally and spatially with Arctic species
- Killer whales are increasingly recorded in the Pacific Arctic
- Anadyr Strait is a marine mammal hotspot for many species of marine mammal, including both Arctic and subarctic species.
- Hundreds of ships tracked by AIS passed by the western side of Saint Lawrence Island from June to November in both 2017 and 2018
- Bearded seals are commonly heard when sea ice concentration at the Chukchi Ecosystem Observatory is high. In contrast, walrus are heard at the same location when sea ice concentration is low

Acknowledgements

We thank Captain Eric Piper, the crew of R/V Sikuliaq, Seward Marine Center shore support, and the Sikuliaq technical support team of Steven Hartz, Dan Nabor and Ethan Roth for their fantastic support throughout the program. Given the size and complexity of our experiments and especially our requirements of extensive climate-controlled incubation space, we believe that no other vessel would have been able to support such a wide array of activities and generate such across-the board successes in our field work.

We thank Bill Wiseman and the National Science Foundation for the addition of funded days at sea in 2017, and UAF's Alaska Sikuliaq Program for major support of ship days in 2017 and 2018. We thank Brendan Smith for accompanying us on the ASGARD cruises and providing photo documentation of our work and we thank Danielle Dickson and Matt Baker for guidance and support of the project through all of its phases. We thank all of the Arctic IERP funders for sponsoring the program: the North Pacific Research Board (NPRB), the Collaborative Alaskan Arctic Studies Program (formerly the North Slope Borough/Shell Baseline Studies Program), the Bureau of Ocean Energy Management (BOEM), and the Office of Naval Research (ONR) Marine Mammals and Biology Program for funding the main ASGARD proposal and all associated linked studies and gap projects (grants A91-99a, A91-00a, A94-00, A98-00a, A96, A97, A99).

We acknowledge that our field work was conducted on the waters where traditional subsistence harvest activities have been conducted by Inupiaq, Siberian Yupik, and Yupik peoples, and we thank them for their continued stewardship. Out of the field, our research is also conducted at the University of Alaska Fairbanks Troth Yeddha' campus, on the customary homelands of the Lower Tanana Dene. Robert Sudyam, Craig George and the Alaska Eskimo Whaling Commission provided valuable guidance for helping us avoid conflict with subsistence harvest activities. We thank Opik Ahkinga of Little Diomede for joining both research cruises and contributing as a valued member of the benthic team and for helping us better understand perspectives of the Bering Strait region residents.

Acronyms and Abbreviations

ACCAP	Alaska Center for Climate Assessment and Policy
ACW	Alaska Coastal Water
ADFG	Alaska Department of Fish and Game
AFSC	Alaska Fisheries Science Center
AGU	American Geophysical Union
AMBON	Alaska Marine Biodiversity Observation Network
Arctic IES	Arctic Integrated Ecosystem Survey
Arctic IERP	Arctic Integrated Ecosystem Research Program
AOOS	Alaska Ocean Observing System
ASGARD	Arctic Shelf Growth, Advection, Respiration and Deposition rate experiments project
ASLO	Association for the Sciences of Limnology and Oceanography
ASP	Amnesic Shellfish Poisoning
AURAL	Autonomous Underwater Recorder for Acoustic Listening
AW	Anadyr Water
BOEM	Bureau of Ocean Energy Management
CDOM	Colored Dissolved Organic Matterr
CEO	Chukchi Ecosystem Observatory
CFOS	College of Fisheries and Ocean Science
COAS	College of Earth, Ocean and Atmospheric Science
CPUE	Catch per unit effort
CTD	Conductivity-Temperature-Depth Instrument
DBO	Distributed Biological Observatory
DIC	Dissolved inorganic carbon
ECMWF	European Centre for Medium-Range Weather Forecast
EJ	Exajoules
ELHS	Early life history stages
ESV	Exact sequence variants
IARC	International Arctic Research Center
IARPC	U.S. Interagency Arctic Research Policy Committee
IOS-DFO	Institute of Ocean Sciences, Fisheries and Oceans Canada
ISHTAR	Inner Shelf Transfer and Recycling program
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
K3S	Kitikmeot Sea Science Study (Canada)
LISST	Laser In-situ Scattering and Transmissometry Instrument
LME	Large marine ecosystem
NCP	Net Community Production
NMFS	National Marine Fisheries Service
nMDS	Nonmetric multidimensional scaling
NOAA	National Oceanographic and Atmospheric Administration
NPRB	North Pacific Research Board
NSB-DWM	North Slope Borough Department of Wildlife Management
NSF	National Science Foundation
OBS	Optical backscatter
OMIX	Ocean mixing project (Japan)
ONR	Office of Naval Research
OSU	Oregon State University

Acronyms and Abbreviations (continued)

PACMARS	Pacific Marine Arctic Regional Synthesis
PAR	Photosynthetically Available Radiation
PI	Principal Investigator
PICES	North Pacific Marine Science Organization
PMEL	Pacific Marine Environmental Laboratory
POC	Particulate organic carbon
SEP	Weight-specific egg production
SKQ	Research Vessel Sikuliaq
SST	Sea surface temperature
TINRO	Russian Federal Research Institute of Fisheries and Oceanography
TPM	Total particulate matter
UAF	University of Alaska Fairbanks
UME	Unexplained mortality event
USARC	U.S. Arctic Research Commission
USFWS	U.S. Fish and Wildlife Service
UVP	Underwater Vision Profiler
UW	University of Washington
VNIRO	Russian Federal Research Institute of Fisheries and Oceanography
WHOI	Woods Hole Oceanographic Institute

Preamble

The Arctic Integrated Ecosystem Research Program

The Arctic Integrated Ecosystem Research Program (Arctic IERP, 2016-2021) was motivated by the rapid changes occurring in the waters of the northern Bering and Chukchi Seas. While much research has been done in the region, many important questions remain. As a cohesive research endeavor, the Arctic IERP was designed to address a single, overarching question:

How will reductions in Arctic sea ice and the associated changes in the physical environmental influence the flow of energy through the ecosystem in the Chukchi Sea?

The report you are reading now is one of five final reports from the fieldwork phase of the Arctic IERP (a synthesis phase was initiated in 2022 after the completion of the Arctic IERP field-based projects). This preamble provides a brief overview of the Arctic IERP, both to place each final report in the broader context of the whole program, and to encourage readers to examine the other final reports to learn more about the research that was done. More detailed information about the Arctic IERP can be found at **https://www.nprb.org/arctic-program**.

The spatial domain of interest for the Arctic IERP extended across the Chukchi Sea Large Marine Ecosystem (LME) as redefined by the Arctic Council's Protection of the Arctic Marine Environment (PAME) working group, and the northern Bering Sea (above 61.5° N) as it strongly influences dynamics in the Chukchi Sea from the upstream direction. The main focus has been on the greater Bering Strait region and the Chukchi Sea. The program included the Arctic Basin and Beaufort Sea insofar as processes in the Chukchi Sea are influenced by these adjacent areas.

Development of the Arctic IERP

Before any Arctic IERP research proposals were written, the NPRB administered an assessment program, the Pacific Marine Arctic Regional Synthesis (PACMARS; https://www.nprb.org/assets/uploads/files/Arctic/PacMARS_Final_Report_forweb.pdf), that applied

$1.5M provided by Shell and ConocoPhillips to compile and synthesize existing information about the ecosystem and inform research priorities. This assessment included community meetings in 2013 in Savoonga, Gambell, Kotzebue, Nome, and Barrow (now Utqiaġvik), in which representatives from 17 communities between St. Lawrence Island in the Bering Sea and Barter Island in the Beaufort Sea participated. One major area of emphasis that emerged from these community meetings was concern about food security for the region's residents in light of the rapid environmental changes taking place. Results from the scientific assessment and input provided via the community meetings informed the creation of the Arctic IERP. The PACMARS report informed both the IERP Request for Proposals (https://www.nprb.org/arctic-program/request-for-proposals/) and the submitted proposals.

Following a proposal review process, the Arctic IERP formally began in 2016 with funding from the North Pacific Research Board (NPRB), the Collaborative Alaskan Arctic Studies Program (formerly the North Slope Borough/Shell Baseline Studies Program), the Bureau of Ocean Energy Management (BOEM), and the Office of Naval Research (ONR) Marine Mammals and Biology Program. Generous in-kind support was contributed by the National Oceanic and Atmospheric Administration (NOAA), the University of Alaska Fairbanks (UAF), the U.S. Fish & Wildlife Service (USFWS), and the National Science Foundation (NSF). This coordinated program was developed in cooperation with the Interagency Arctic Research Policy Committee (IARPC) and the U.S. Arctic Research Commission.

The Research

The Arctic Integrated Ecosystem Research Program (IERP) invested approximately $18.6 million in studying marine processes in the northern Bering and Chukchi Seas in 2017-2021, beginning in the summer of 2017. The research was divided into three main, complementary projects. The Arctic Shelf Growth, Advection, Respiration, and Deposition Rate Experiments (ASGARD) project carried out research in late spring and early summer of 2017 and 2018 aboard R/V Sikuliaq. The Arctic Integrated Ecosystem Survey (Arctic IES) conducted fieldwork aboard R/V Ocean Starr in late summer and early fall 2017 and 2019. In addition to the vessel-based surveys, sub-surface moored sensors were deployed to gather biophysical information continuously from June 2017 to September 2019.

In addition to the vessel-based work, a team of Arctic residents and social scientists, including members from eight communities in the North Slope and Northwest Arctic Boroughs and the Bering Strait region, met several times during the project to assess and analyze Indigenous observations and experiences with various types of change occurring in the region from Savoonga to Utqiaġvik. This group also compiled an annotated bibliography of Traditional Knowledge or Indigenous Knowledge (available through the data portal described below), to help researchers from other components of the Arctic IERP find information relevant to their studies.

Prior to the commencement of fieldwork, meetings were held in the three hub communities of Nome, Kotzebue, and Utqiaġvik. Scientists from the Arctic IERP and NPRB staff met with community members from each region to discuss the research purpose and plans. Research plans were also shared and discussed at meetings of the Alaska Eskimo Whaling Commission (AEWC), the Indigenous Peoples Council for Marine Mammals (IPCoMM), and with the Tribal Councils of Gambell and Savoonga on St. Lawrence Island. One result of these meetings was a shift in timing of the ASGARD cruises from May until June as well as a shift in timing and survey regions for the Arctic IES cruises, to avoid conflicts with subsistence hunting activities during what is traditionally the time for walrus hunting. Another result was the creation of communication protocols to avoid conflicts by alerting coastal communities to the presence of research vessels and adjusting the ships' routes to avoid areas where hunting was taking place. These communication protocols included regular radio broadcasts and daily emails to community members throughout the research area.

Results from the research are published in a growing list of peer-review journal articles, as well as cruise reports that provide contemporary accounts of the cruises, and many social media postings that are available through the NPRB website. Data are publicly available as described below.

Collaborations

The NPRB collaborated and coordinated with several other U.S. agencies and organizations that fund Arctic marine research. NPRB staff worked closely with the U.S. Interagency Arctic Research Policy Committee (IARPC) and the U.S. Arctic Research Commission. As the Arctic IERP was developed, the NPRB secured commitments for collaboration from 22 existing research projects that were detailed in Appendix A of the request for proposals, and made connections with new projects as they were funded.

International researchers also collaborated with the Arctic IERP via the Pacific Arctic Group (PAG), the North Pacific Marine Science Organization (PICES), and the Intergovernmental Consultative Committee (US/Russia - bilateral) as well as collaborations developed by individual investigators. PAG participants, including researchers from Canada, China, Japan, Korea, Russia, and the United States, have coordinated their cruise plans to sample standard stations in the Chukchi and Beaufort Seas termed the Distributed Biological Observatory (DBO). The Arctic IERP contributed to this effort. US-Russian data sharing initiatives were hosted in San Diego in 2016 and Vladivostok in 2017 to promote collaboration and exchange and to facilitate collaboration and synthesis of data and trends of patterns observed in the US and Russian waters in the northern Bering and Chukchi seas (PICES Press, Volume 26, Issue 1). ICC collaborations and other connections also brought scientists from the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO), the Russian Pacific Scientific Fisheries Research Center (TINRO), and Hokkaido University to the US to participate in the Arctic IES cruises and co-author results. This collaboration is expected to connect research interests within respective EEZs (Russia/US) of the Chukchi Sea.

COVID-19

While the fieldwork of the Arctic IERP was completed before the outbreak of COVID-19, the final meeting of researchers in November 2020 was changed from an in-person event to an online format. Other plans for in-person events, such as meetings in hub communities within the US Arctic region (Nome, Kotzebue, and Utqiaġvik), were cancelled. Laboratory work and some collaborations were postponed or cancelled due to COVID-related restrictions and concerns. The NPRB made supplemental funds available to assist researchers with unanticipated expenses due to the pandemic. The overall productivity of the Arctic IERP was likely not greatly reduced, due both to good fortune in the fieldwork being completed and to the collaborative relationships that had been built or strengthened during the program.

Data Portal

Axiom Data Science, Inc. provided data management support to the Arctic IERP throughout the field program. Axiom staff assisted the scientists in authoring metadata and publishing the datasets to public archives. The data collected by the Arctic IERP are publicly accessible at **https://arctic-ierp.dataportal.nprb.org/**

General Introduction

ASGARD Background & Scientific Rationale

As a changing climate and sea-ice retreat progressively expose the Chukchi Sea to a longer open water season, society will confront new resource management issues. These include the future of the cultures and subsistence lifestyles of local indigenous communities, potential impacts of industrial activities (e.g. commercial fishing, oil and gas extraction), potential changes to regional ocean carrying capacity, and resilience of the Arctic marine ecosystem (NRC, 2014).

An ecosystem-based approach is needed to inform and guide policy-driven actions but this approach requires synthesis of a detailed knowledge base that today remains incomplete in three important ways. First, existing data are strongly biased to July through October although important ecosystem processes occur in spring, late fall and winter when access is difficult. Second, while we now understand the basic summer regional biogeography (Sigler et al., submitted), net community production (Codispoti et al., 2013), and drivers of species distributions for some taxonomic groups (Feder et al., 1994; Eisner et al. 2013; Blanchard, 2014; Grebmeier et al., 2015a; Ershova et al. 2015), we have scant information from any season about the fundamental chemical and biological rates that mediate carbon cycling and energy flows through the ecosystem. Third, these knowledge gaps curtail our ability to model the ecosystem with even a basic level of confidence – and our ability to make useful projections upon which we can base management or policy decisions.

The ASGARD project addressed the above limitations by:

1. Coordinating and collaborating with other ongoing projects, including participating in ship-of-opportunity sampling later in those years; and
2. Carrying out year-round biophysical mooring deployments.

With this approach, we gathered critically missing information required for modeling and follow-on synthesis activities, such as sought by Gibson and Spitz (2011) and Whitehouse et al. (2014). As shown in this report, some of these synthesis analyses have already been begun in the course of our initial publication efforts. Although the Arctic IERP program as a whole has advanced our understanding, the analyses that we might approach today include new questions that were not well appreciated just a few years ago when the program began.

The Arctic is experiencing rapid and extreme changes. The Pacific Arctic Region (PAR), which includes the Bering Strait region, and Chukchi and Beaufort Seas, is a bellwether for these changes with sea ice extent and thickness decreasing and freshwater and heat content increasing (i.e. Stroeve et al. 2012, Woodgate et al. 2012). The biological responses to these extreme physical changes are complex but may result in a shift in the northern Bering Sea and Bering Strait from an Arctic-type ecosystem to a subarctic-type ecosystem (Grebmeier et al. 2006b, Grebmeier 2012). One way to monitor changes in, or impacts on, an ecosystem is to observe the response of a suite of upper trophic level species such as sea birds and marine mammals via changes in occurrence and/or distribution (Moore et al. 2014). For instance, the PAR ecosystem "reorganization," from benthic- to pelagic-based, might negatively impact marine mammal species that rely on sea ice for habitat (e.g. Ice seals, walrus, bowhead whales) and/or benthic infauna for food (e.g., walrus, gray whales, some ice seals) via a reduction in habitat and prey abundance (Grebmeier et al. 2006a). Other species, however, such as sub- Arctic "summer whales" may benefit from increased access to northern habitat and pelagic prey species (Moore and Huntington 2008, Clarke et al. 2013).

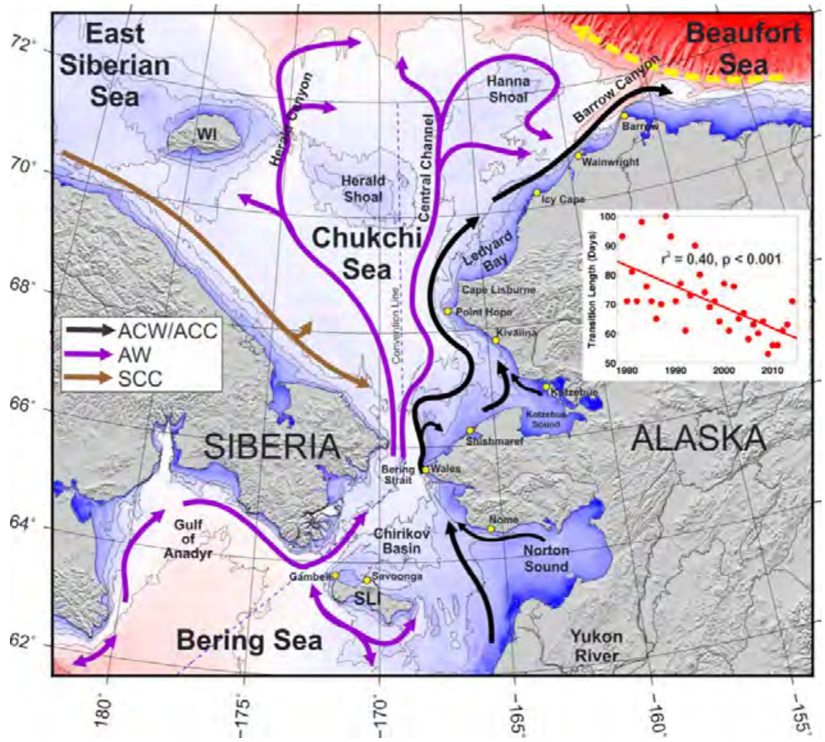

Figure 1. Map showing place names, persistent current systems, bathymetry (color shading). Inset: Decline in the regional duration of the annual spring sea-ice retreat, computed as the time between 80% and 20% ice cover.

While the risk of potential competition for resources from sub-Arctic species expanding northwards is poorly understood (Clarke et al. 2013), integrating upper trophic level species with environmental data can provide insight into those environmental drivers result in increased competition. Further, assessment of impacts of increased human activities in the arctic (marine resource extraction and increased shipping) requires improved basic marine mammal population information (Reeves et al. 2013). Finally, there is concern among native Alaskans who live in the villages of the Arctic that environmental changes may result in changes in distribution of, and access to, species that are important for subsistence.

As the only oceanic gateway between the Pacific Ocean and the Arctic, the Bering Strait and Chukchi Sea are regions where climate change and changing anthropogenic utilization may have sizeable impacts on local marine fauna, and where changing fluxes of marine mammals to the Arctic can be confidently observed. The PAR is home seasonally to vocal Arctic species such as bowhead and beluga whales; bearded, ribbon and ringed seals; and walrus. Bowhead whales are currently listed as endangered species and walrus have been proposed for a “threatened” listing due to decreasing sea ice cover in the Arctic. In the summer, the northern Bering and Chukchi Seas provide habitat for fin, humpback, minke, gray and right whales (Clarke et al. 2013). Gray whales are regularly seen in the PAR and there have been recent sightings of humpback and fin whales north of the Bering Strait but relatively little is known of the northern limits of distribution for these “summer” whales.

The Bering Strait acts as a gateway for migration of animals between the Pacific Ocean and Bering Sea and the Pacific Arctic. The Bering Strait region is ice covered (i.e. those closed to marine mammals which need access to the surface to breathe) in the winter and “reopens” in the late spring, thereby influencing the migratory patterns of many marine mammal species (e.g., bowhead, beluga and gray whales, ice seals). Traditionally viewed as simply a route through which animals migrated, it is slowly becoming clear that marine mammals may spend significant portions of the summer and autumn in the PAR if prey is available there (Clarke et al. 2013; Lowry et al. 1980)

Flow from the Pacific advects nutrients and plankton into the Arctic Ocean, supporting very high levels of seasonal productivity that differ in the eastern and western PAR. The Bering Strait is the only source of Pacific inflow to the Arctic and has been the focus of ongoing research seeking to characterize circulation in the Arctic in light of global climate change (e.g., Aagaard al. 2006; Woodgate et al. 2005a, b; Woodgate et al. 2006, 2012). Pacific waters are a key source of nutrients for the Arctic Ocean (e.g., Walsh et al 1989), Therefore, in the PAR has important implications for Arctic biology, circulation, and the global freshwater budget (Woodgate et al. 2005b, 2006, 2012) and for the feeding success of marine mammals (Berline et al. 2008, Eisner et al. 2013). Differences in the physical oceanographic environment from east to west suggest that monitoring both sides of the PAR is critical to fully understanding changing ecosystem dynamics.

Changes in the timing and extent of annual sea ice influence the community ecosystem dynamics of this region. Ecosystem composition is affected directly via opening or closing of the strait and indirectly through the export of primary production to the shallow benthos (Grebmeier et al. 2006b). If the retreat of seasonal sea ice continues to shift the subarctic-Arctic temperature front, then community composition in the northern Bering and Chukchi Seas is likely to change, if not permanently, then seasonally (Overland and Stabeno 2004; Grebmeier et al. 2006a).

The PAR is home to native Alaskan and Russian communities that rely on marine mammals for subsistence. A recent workshop held in Nome, Alaska (Cooper 2010) identified the most pressing scientific questions to be addressed in the Bering Strait region from the perspective of local stakeholders (village inhabitants). Of highest priority for this group was increased monitoring of marine mammals, via visual and acoustic observations, because Arctic species and food security are vital to their survival.

As seasonal sea ice continues to diminish, ambient noise levels from shipping and seismic exploration will increase. As the Northern Sea Route and Northwest Passage become viable Pacific-Atlantic shipping routes, every ship along this route will pass through Bering Strait. The number of ships scheduled to use the Northern Sea Route increased dramatically from 4 in 2011 to 200 in 2013. This will lead to an inevitable increase in ambient noise levels at the low frequencies used by baleen whales, thereby decreasing the range over which they communicate and increasing the possibility of ship strikes (Clark et al. 2009; Hatch et al. 2012).

One means of assessing changes in marine ecosystems (the physical environment can be measured directly) is to examine the distribution of fauna that are directly influenced by such changes (Moore et al. 2014). As the top of short Arctic food webs, marine mammals can be considered sentinels of environmental change (Moore 2008; et al. 2014). Changes in cetacean abundance and distribution have been shown in conjunction with short and long time scale climate events in the north Pacific (Benson et al. 2002; Fiedler 2002; Croll et al. 2005) and Bering Sea (Stafford et al. 2010). Passive acoustic sampling is extremely robust, and can detect the presence of vocalizing marine mammals continuously (24 hours a day) in any weather conditions over weeks to months, over a distance of some 20-30 km and is a proven sampling method in waters offshore Alaska (Moore et al. 2006, 2012), including the Beaufort Sea and Chukchi Seas (Hannay et al. 2012, MacIntyre et al 2013; Stafford et al. 2007, 2013).

Species-specific characteristics of marine mammals vocalizations allow for unambiguous identifications based on acoustic signatures (Thomson and Richardson 1995). Therefore, acoustic monitoring can provide the ability to determine which species are present at a given time, and how species composition changes across seasons in the Bering and Chukchi Seas. For instance, gray whales, which have recently been regular summer visitors to the western Beaufort Sea, were detected even in mid-winter in 2003-2004 by use of acoustic recordings (Stafford et al. 2007) and fin and humpback whales have been recorded in the Chukchi Sea (Delarue et al 2013; Hannay et al. 2013).

At present, the Arctic Ocean has relatively low ambient noise levels in winter due to ice cover that reduces wind waves (Milne and Ganton 1964; Roth et al. 2012) and in summer primarily due to the lack of commercial shipping, which has increased ambient noise levels significantly in other oceans (MacDonald et al. 2008). The reduction in seasonal sea ice and expansion of the open water season will change the seasonal ambient noise cycles of the Arctic. In late summer and fall, as the Northwest Passage and Northern Sea Route become viable Pacific-Atlantic shipping routes, every ship along this route will pass through Bering Strait resulting in increased ambient noise levels at the low frequencies used by baleen whales. In addition to anthropogenic increases in noise, the longer open water season and increasing storminess of Arctic regions (Overland et al. 2014; Thomson and Rogers 2014) will also lead to higher noise levels. Increases in ambient noise levels elsewhere have been shown to decrease the range over which marine mammals can receive signals, increase stress levels and change behavior (Richardson et al. 1986; Hatch et al. 2012; Rolland et al. 2012). While these reactions can be difficult to discern, long-term ambient noise data can be used to monitor ship passages, industrial exploration and storms.

Integration of acoustic detections of marine mammals is increasingly being used to understand correlations between habitat variables, prey, and marine animal presence. These include the use of generalized linear models, generalized additive models and time series analysis among others in order to determine what environmental factors most influence the presence of animals. In this manner, it may be possible to predict how the behavior of different species will change under changing environmental conditions (Baumgartner and Fratantoni 2008; Stafford et al. 2009, 2013; MacIntyre et al. 2015; Baumgartner et al, 2014).

In the shallow waters of the Chukchi and northern Bering Seas, low frequency acoustic signals from marine mammals (fin, bowhead, gray whales) are unlikely to transmit more than 20 km and higher frequency signals (from ice seals and beluga whales) will likely only be detected 5-10 km away. Therefore, the same signals will not be detected on multiple hydrophones. Each instrument will thus record signals local to the mooring area allowing comparison of the three proposed locations over the same time scales. When data from similar instruments deployed in Bering Strait and north of the Strait (Figure 1) are contributed, we will have coverage of all gateways between the Pacific and the Arctic Ocean. This will allow us to map migratory pathways and timing of the different species that use the Pacific Arctic.

By deploying acoustic recorders on biophysical oceanographic moorings, we can examine relationships between the physical and biological drivers in the PAR and quantify the animal fluxes in a manner that allows the investigation of seasonal and interannual change and understand the levels of underwater noise in the Arctic.

The ASGARD project is a coordinated ensemble of vessel- and mooring-based process studies consisting of physical, chemical, biological, and biogeochemical rate measurements that are designed to better constrain our understanding of carbon and nutrient dynamics of the northern Bering and Chukchi sea continental shelves.

Project Objectives

The ASGARD program was designed to address the NPRB Arctic Program's overarching questions outlined in their Request for Proposals: "How do physical, biological and ecological processes in the Chukchi Sea influence the distribution, life history, and interactions of species or species guilds critical to subsistence and ecosystem function? How might those processes change in the next fifty years?". Specific objectives that used passive acoustic monitoring data include

- **O-1:** *Deploy hydrophones on 3 moorings in the northern Bering and Chukchi Sea.*
- **O-2***: Document the inter-seasonal and inter-annual presence of vocal marine mammals in the Pacific Arctic Region and compare of acoustic detections in the eastern, western, and central PAR.*
- **O-3:** *Integrate oceanographic drivers with acoustic detections to better understand how the physical environment influences the biological inhabitants of that environment*
- **O-***4:* *Collaborate with other ASGARD PIs to develop an integrated understanding of the ecosystem components of the Pacific Arctic Region from physical forcing through to upper trophic level consumers.*

Approach

The ASGARD study consisted of ship-based and mooring-based studies designed to integrate with other proposed field, modeling, and human dimensions efforts. We selected the following focal measurements to help us address our main science question:

- Advective fluxes of physical, biotic and abiotic components of the water column
- Phytoplankton primary productivity
- Zooplankton growth/reproduction, respiration and fecal pellet production rates
- Particle deposition rates from the water column to the seafloor
- Quality of organic matter deposited to the seafloor
- Benthic respiration and organic matter decomposition rates
- Abundance and biomass of benthic microbial and metazoan fauna
- Distribution of fishes at different life history stages (NPRB Award A98-00a)
- Underwater sound and seasonal distributions of marine mammals (NPRB Award A94-00)

We sailed to the northern Bering and southern Chukchi shelf in 2017 and 2018 (Figure 2) on *R/V Sikuliaq*. In each year, working south to north, we first occupied ten "process" stations (yellow squares in Figure 2). As the ship visited the process stations, we paused to deploy and/or recover moorings (Figure 2) that recorded year-round time-series. Throughout the cruise we collected continuous underway navigational, ocean surface, ocean profile, and meteorological data and marine mammal observations (Figure 3) to provide additional environmental context for subsequent analyses.

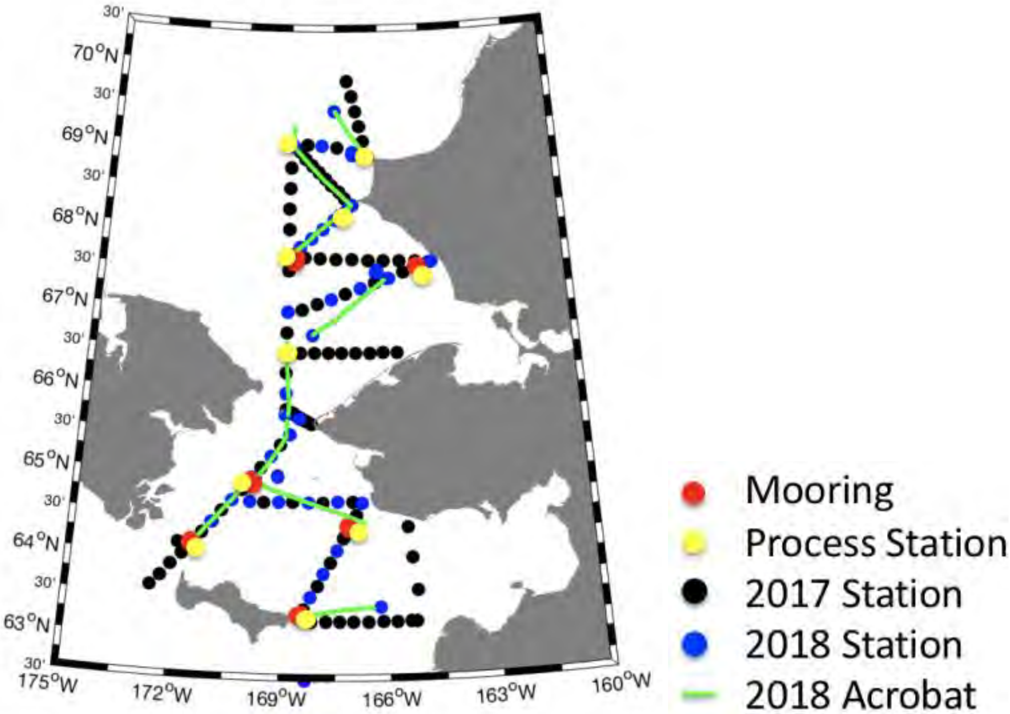

Figure 2. Location of field effort. Most 2018 stations (blue circles) were also occupied in 2017 (black circles). Some circles were shifted slightly on the map to reduce overlap.

The mooring array (Figure 2) consists of four biophysical moorings south of Bering Strait, two moorings in the southern Chukchi Sea plus the NPRB Long-Term Monitoring Program NE Chukchi Sea Ecosystem Mooring located on the southern flank of Hanna Shoal near Barrow Canyon. Together, these seven moorings allowed us to examine cross-shelf differences between the AW and ACW regimes and physical and biogeochemical changes imparted as the waters flow across the shelf into the Arctic. These instruments recorded year-round to reveal time histories of: nutrient and phytoplankton concentrations and fluxes; the bifurcation of flow to either side of St. Lawrence Island and the influence of regional winds on the upstream structure and partitioning of water masses feeding Bering Strait; conditions in Anadyr Strait, in the nexus of the most important zone at which subsurface nutrients are mixed to the surface as they arrive at Chirikov Basin and Bering Strait; AW and ACW properties and advection rates; phytoplankton blooms, sinking organic matter fluxes and their relationship to advective supply, light, ice thickness and the retreating ice edge; bottom sediment resuspension with respect to water and ice motion and ambient noise.

In addition, we aimed to contribute to the graduate educations of PhD students, including two students partially funded by the project and students not requiring financial support from ASGARD, but who participated in our cruises and collected data for use in their externally-supported research. We sought to strengthen existing and build new collaborations with national and international partners. We had cruise involvement of outreach specialists to help us communicate our science to targeted stakeholders and the public. We strengthened our ties to the coastal communities by participating in numerous co-management and other Alaskan Native

Organization meetings, including Tribal Council consultations and the incorporation of a local observer on board our research cruises.

Field Expeditions

ASGARD field efforts (Figures 2 and 4) are documented in two detailed scientific cruise reports (Danielson et al., 2017; 2018) and one community observer report (Ahkinga, 2017) that are available at the NPRB Arctic IERP website: https://www.nprb.org/arctic-program/about-the-program/. The cruises took place in June 2017 and June 2018. We joined the Arctic EIS component of the IERP for final mooring recoveries in August 2019. Weather conditions and cruise timing allowed us to occupy more survey stations in 2017 than in 2018.

Emerging Stories

This report documents ASGARD project activities and results through the end of the initial phase of research and analysis (2016-2021). We were successful in collecting data that has been and will be applied to all of our focal objectives and hypotheses, and, as shown below, we addressed each from several vantage points. At the same time, we have only scratched the surface of the vast suite of potential results that the rich Arctic IERP dataset will yet reveal.

The *Results* section chapters document observations, and analyses that use data collected in the ASGARD field effort and were written in support of helping fill the three main information gaps identified in the ASGARD proposal (i.e., seasonal data gaps, rate measurements, and model parameterization/validation data) and guiding science question (i.e., ecosystem change in the face of diminishing sea ice). These chapters include graduate student dissertation chapters, and peer-reviewed journal articles (published and in preparation) that were written in support of the ASGARD project proposal and the Arctic IERP Integrated Work Plan (NPRB, 2016).

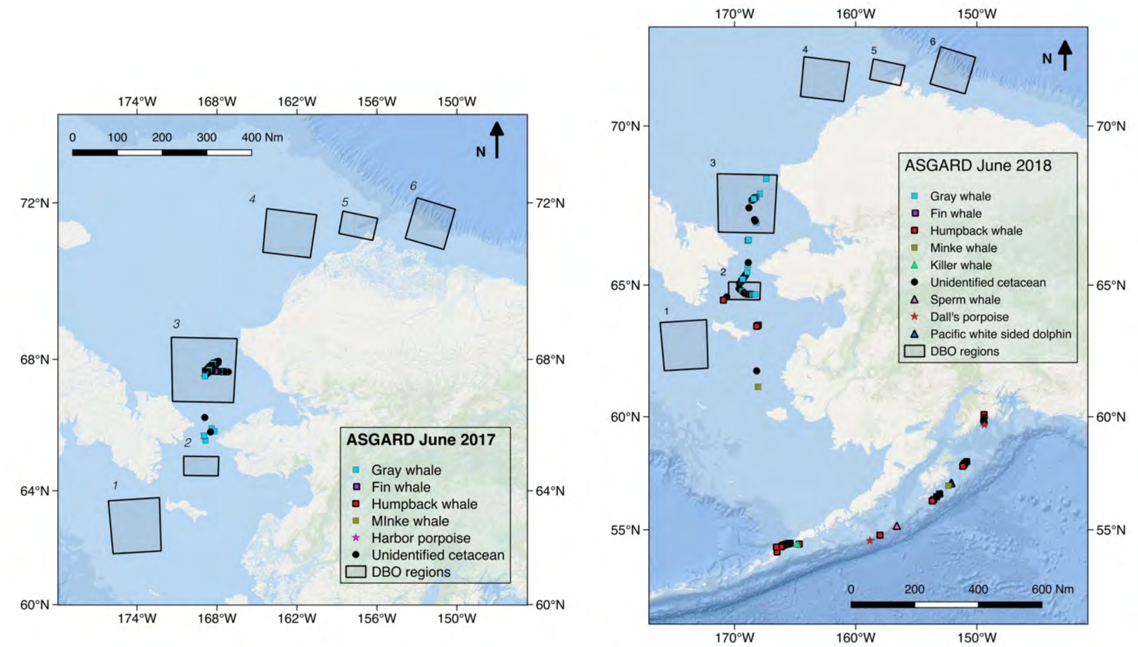

Figure 3. Left panel shows marine mammal sightings during the ASGARD 2017 cruise as well as Distributed Biological Observatory locations. Right panel shows sightings from the 2018 cruise.

Chapters are organized as follows. Chapters 1-3 concentrate on marine mammal occurrence and environmental conditions (physics and biology) and their temporal and spatial variability. Chapters 1-3 presents information on the seasonal and spatial occurrence of marine mammals in the ASGARD study area and the interaction of these with environmental conditions. Chapter 4 examines the long-term changes in marine mammals at the Chukchi Ecosystem Observatory. Chapter 5 presents information on the underwater soundscape and ship noise contributions to the northern Bering Sea. Chapter 6 is a review of changes in subarctic upper trophic level distributions. Chapter 7 (cited as Chapter 19 in the Danielson report) raises the question of whether this highly productive ecosystem could be in the midst of a significant ecological transformation.

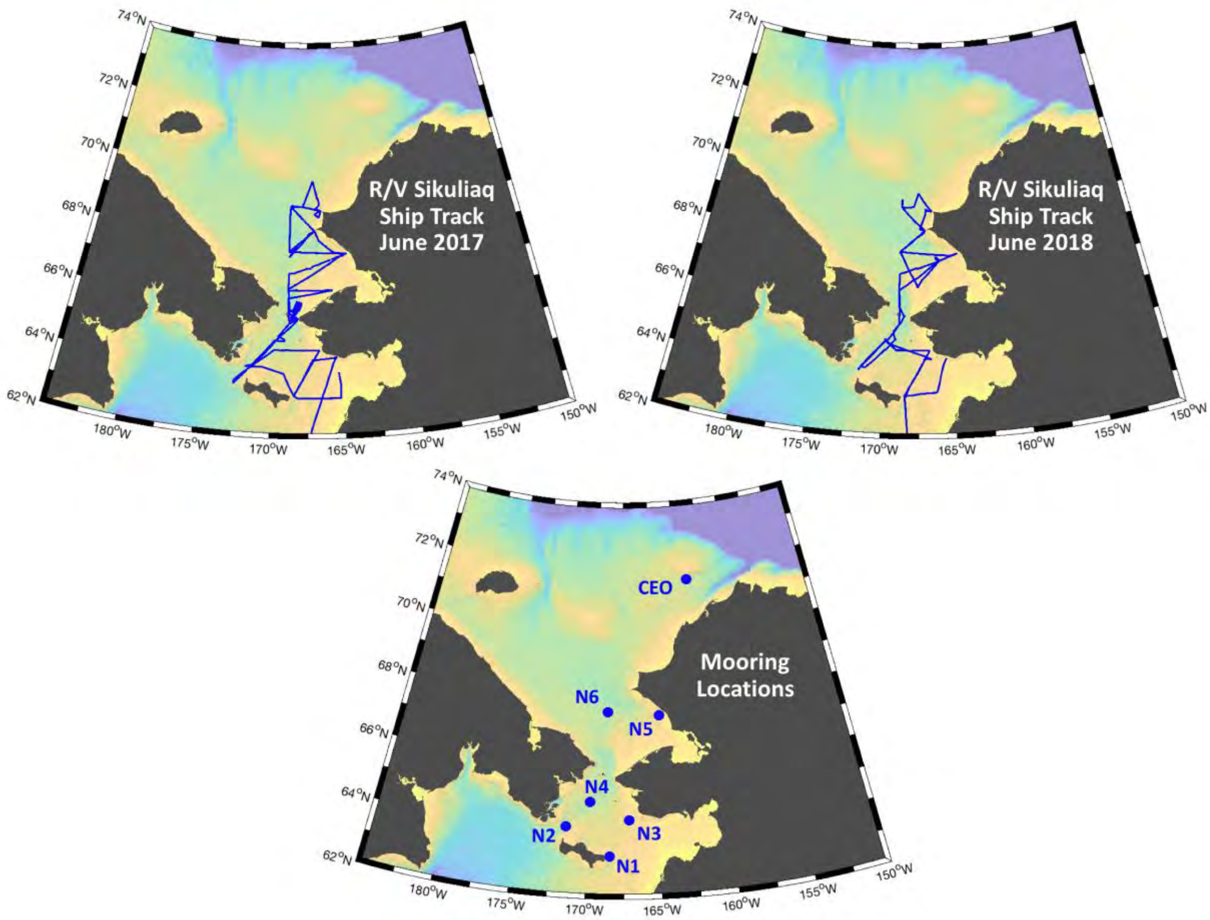

Figure 4. Vessel track lines (blue) for cruise SKQ2017-09S (June 2017, upper left), SKQ2018-13S (June 2018, upper right) and year-round mooring locations (blue circles, bottom). Identifying names for ASGARD moorings N1-N6 and the Chukchi Ecosystem Observatory (CEO) mooring cluster are labeled.

Results

Chapter 1: Characterizing spatio-temporal patterns in the acoustic presence of subarctic baleen whales in the Bering Strait in relation to environmental factors

Escajeda, E, Stafford KM, Laidre KL, Woodgate R. *in prep*

This chapter will form part of the PhD dissertation of Erica Escajeda at the University of Washington.

Subarctic baleen whales, namely humpback whales (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*), are common summer visitors to the Pacific Arctic, migrating through the Bering Strait and into the southern Chukchi Sea to feed on seasonally-abundant prey. The abundance and distribution of fin and humpback whales in the Chukchi Sea varies from year-to-year, possibly reflecting fluctuating environmental conditions. Using acoustic recordings from three moored hydrophones in the Bering Strait from 2009–2018, we identified whale calls during the open-water season (May–November) and investigated potential environmental drivers of whale presence. We examined *in-situ* temperature, salinity, wind and water velocities measured in the strait, as well as satellite-derived sea surface temperatures. Our results show significant interannual variability with the greatest number of hours with calls in years with contrasting environmental conditions: 2009 and 2017 for humpback whales, 2012 and 2015 for fin whales. Separate zero-one inflated beta models were fit for each species and year using the proportion of hours per day with whale calls as the response variable. Each model identified different significant environmental predictors, suggesting that environmental determinants of whale acoustic presence may change year-to year. Most hours with whale calls (humpback: 61%; fin whales: 91%) were recorded at the mooring site nearest the confluence of the nutrient-rich Anadyr and Bering Shelf water masses, indicating that these productive water masses may influence the occurrence of humpback and fin whales. The disparity in conditions between years suggests there may be multiple combinations of environmental factors or other unexamined variables that draw subarctic baleen whales into the Pacific Arctic.

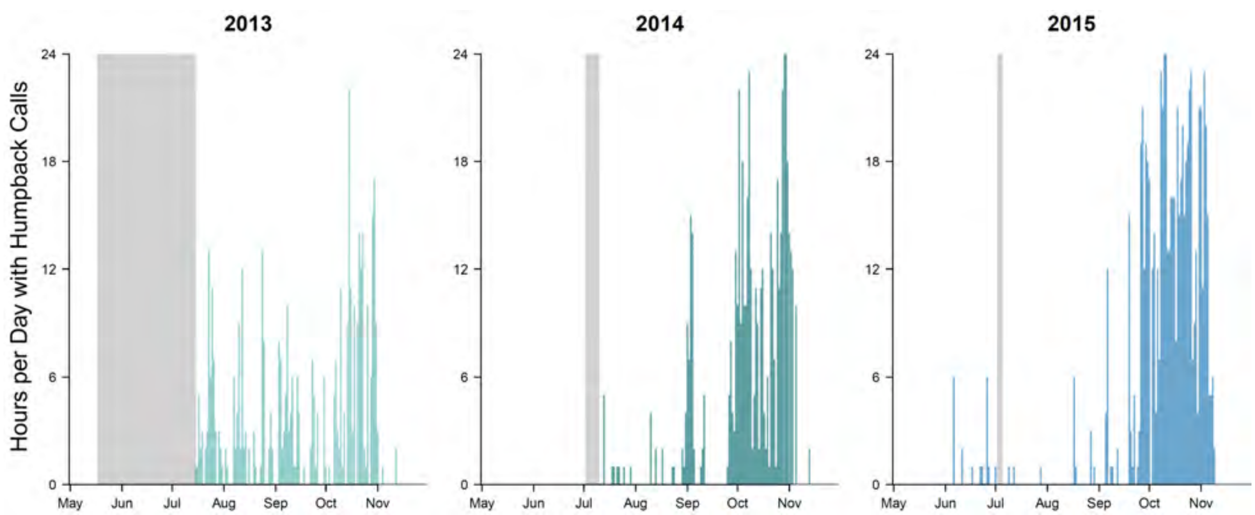

Figure 5. Number of hours per day with humpback whale calls from mooring A3 just north of Bering Strait.

Chapter 2: Acoustic identity of killer whales recorded on hydrophones in Anadyr Strait

Stafford, K.M., Wallace, E.E. *in prep*

Killer whales are being increasingly seen and heard in the Arctic as seasonal sea ice decreases. Recordings of killer whales from hydrophones in the northern Bering and southern Chukchi Sea will be characterized by their time and frequency contours and compared to known killer whale repertoires to describe the repertoire of Arctic killer whales. This project will entail the use of passive acoustic analysis software to categorize call types using standard killer whale acoustic terminology. Different "bouts" of calling will be compared to see if there are similarities/differences among them and if they can be identified to eco-type.

Killer whales were recorded at all sites in the northern Bering and southern Chukchi Sea from June through December (Figure X). There were not heard on the AON site which is at 152° W in the Beaufort Sea. Most of the call types were identified as transient, or mammal eating, killer whales based on the characteristics of their calls (Figure Y).

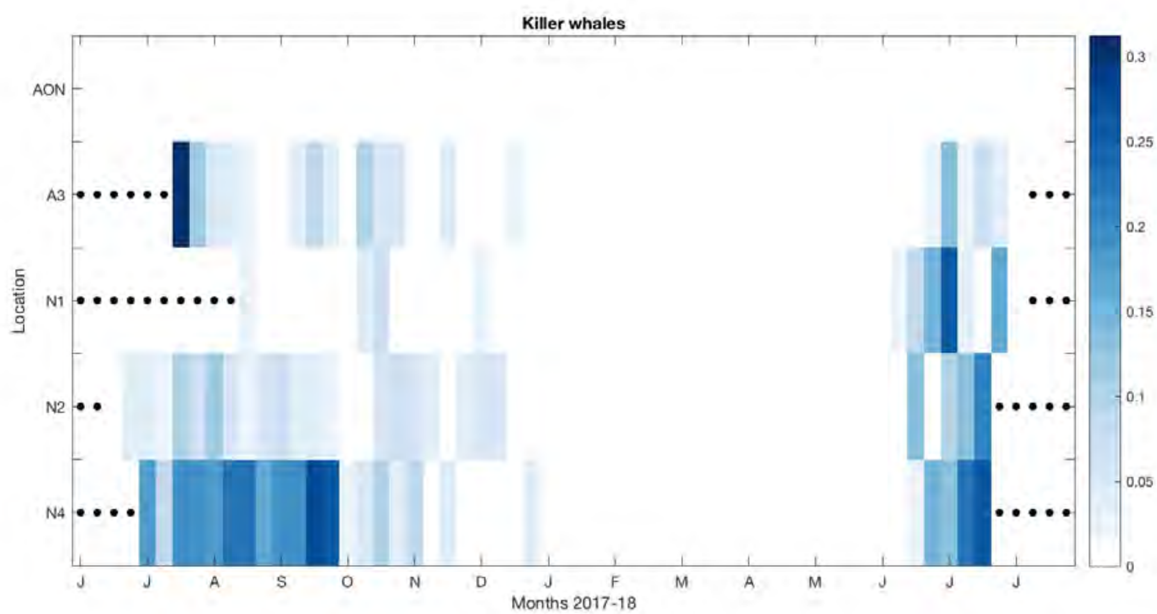

Figure 6. Seasonal occurrence of killer whale acoustic detections from 5 locations spanning the northern Bering (M1, N2, N4), southern Chukchi (A3) and western Beaufort Sea (AON) from June 2017 to June 2018.

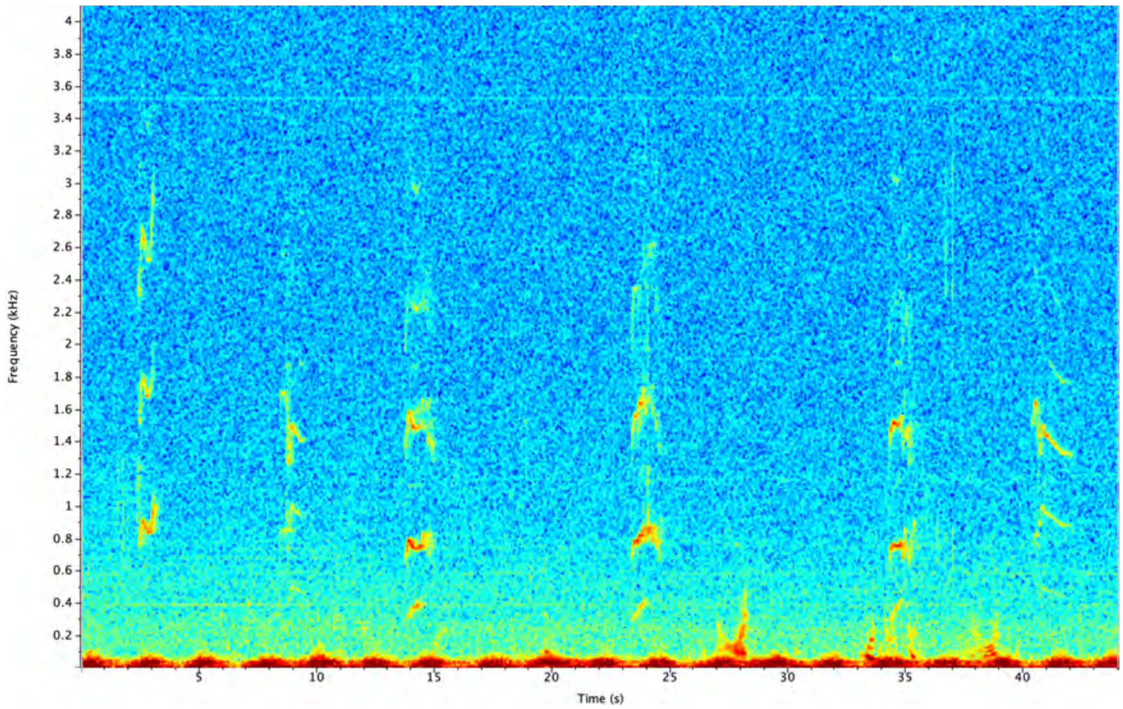

Figure 7. Spectrogram of 6 killer whale calls recorded on 13 July 2017 at ASGARD mooring N4.

Chapter 3: Seasonal and geographic variation of marine mammals in the northern Bering Sea

Stafford, K.M., Danielson, S.L. *in prep*

The Pacific Arctic Region (PAR), which includes the Bering Strait region, and Chukchi and Beaufort Seas, is a bellwether for climate change in the Arctic with sea ice extent and thickness decreasing and freshwater and heat content increasing. In 2017-2018, the PAR experienced extreme warming evidenced by high water temperatures and greatly reduced seasonal sea ice in the northern Bering and Chukchi Seas. The biological responses to these extreme physical changes are complex but may result in ecosystem shifts from primary productivity to upper trophic predators. To observe the response of upper trophic level species via changes in occurrence and/or distribution over both temporal and spatial scales, passive acoustic recorders were deployed on three ecosystem moorings in PAR hotspots: the northern Bering Sea off western St Lawrence Island, in the Chukchi Sea at Hanna Shoal, and on the shelf break of the western Beaufort Sea from 2017-18.

The furthest south hydrophone (Bering Sea) had the greatest seasonal occurrence of both subarctic and Arctic species; while these species suites had peak occurrences during different seasons, there was nevertheless extensive overlap in early winter of fin, humpback and bowhead whales. This overlap and overall community compositions decreased further north such that the only subarctic species detected in the Beaufort Sea was killer whales, which appear to have extended their distribution both northwards and eastwards into the Beaufort Sea. The Arctic endemic species bowhead and beluga whales were each detected later in the fall and winter and earlier in the following spring along their migratory route in the Chukchi and Beaufort Seas. Changes in sea ice extent and seasonality are the most obvious drivers of the presence/absence of marine mammal species in the PAR. Understanding how these broad changes impact the smaller scale physical and lower trophic level biological environments that influence the phenology, residence time, and community composition of marine mammals, may shed light on whether an ecosystem transformation is underway in the Pacific Arctic.

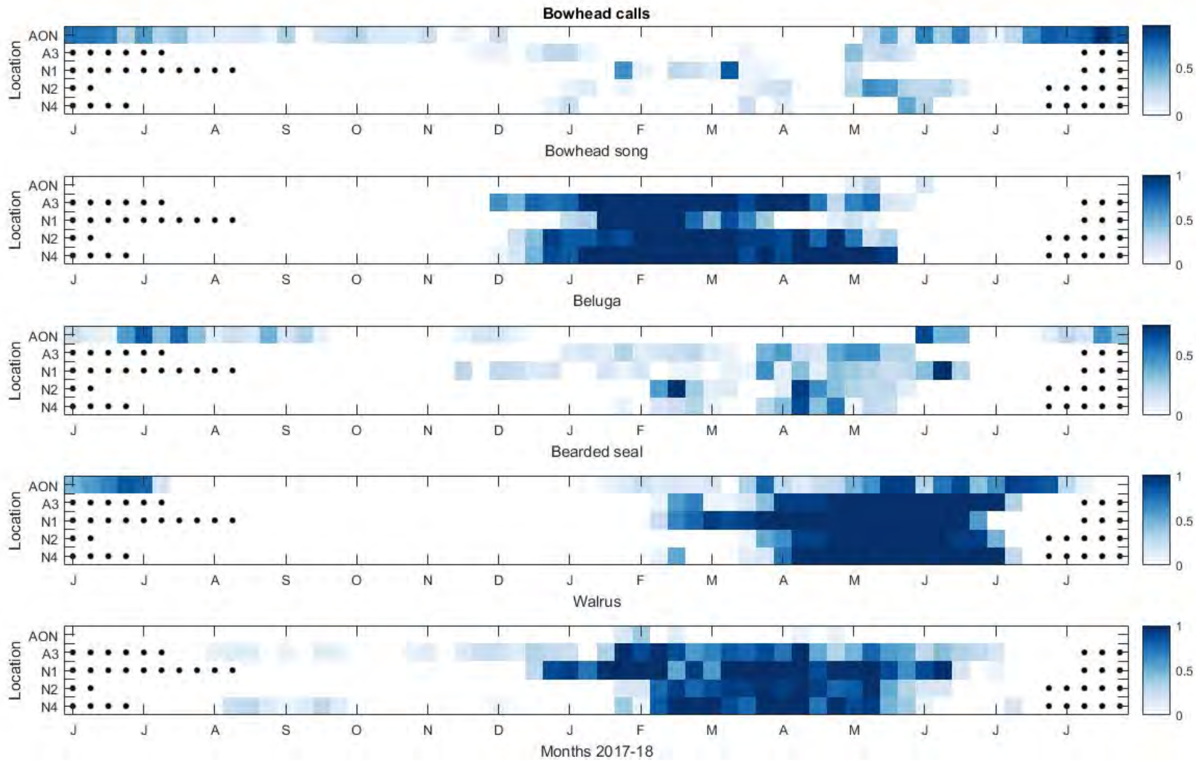

Figure 8. Seasonal occurrence of Arctic marine mammals from northern Bering Sea (N1, N2, N4) through the Bering Strait (A3) and into the Beaufort Sea (AON). Black dots indicate periods with no data.

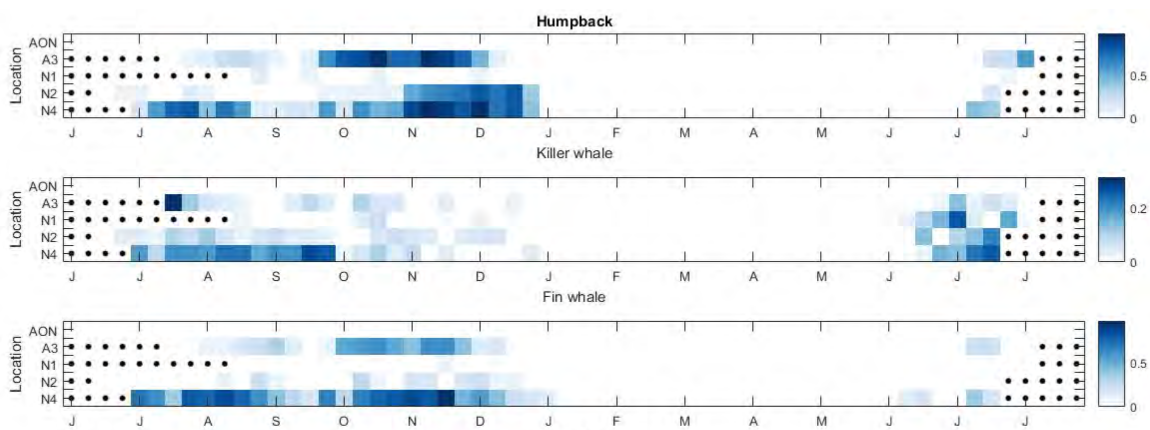

Figure 9. Seasonal occurrence of subarctic marine mammals from northern Bering Sea (N1, N2, N4) through the Bering Strait (A3) and into the Beaufort Sea (AON). Black dots indicate periods with no data.

Chapter 4: Long-term marine mammal occurrence at the Chukchi Ecosystem Observatory

Stafford, K.M., Danielson, S.L., Escajeda, E. *in prep* Walrus and Bearded Seal Detections at the Chukchi Ecosystem Observatory 2015-2020

The Arctic as we know it is experiencing changes that range from invasions from subarctic species, changes in phenology of arctic species, and changes in Arctic food webs. The added pressure of increased economic ventures highlights the urgent need for long-term observations in the Arctic Ocean, including changes in biodiversity. Chukchi Ecosystem Observatory (CEO) was established in 2014 to provide year-round observations of core physical, chemical and biological processes in the Arctic. The CEO mooring is located in the biological "hotspot" located on the NE Chukchi Sea shelf near Hanna Shoal, where a thriving benthic community supports a major walrus foraging ground during summer and fall months. Beginning in 2015, a passive acoustic recorder was added to monitor the presence of vocal marine mammals and the overall Essential Ocean Variable of 'sound.'

The instrument was programmed to record acoustic data from 10 Hz to 8 kHz on a 25% duty cycle (the first 15 min of every hour). Upon recovery, the data were visually and aurally examined to determine the presence/absence of walrus and bearded seal vocalizations. Each of these species contribute significantly to the overall underwater soundscape at the CEO but at different times of the year. Walrus sounds started in late May, when sea ice concentration began to abruptly decrease and were heard continuously until early November annually. Walrus vocalizations ceased 1-3 weeks before sea ice began to form in autumn. In contrast, bearded seals were only seldom heard during the open water period, but their vocalizations were recorded 24h/day as soon as sea ice concentrations increased to over ~75% in early December. Bearded seal trills were heard through late June/early July and declined with sea ice concentration with the exception of 2019 when there was little or no ice at the CEO from late May to mid-June, when bearded seals were nevertheless recorded at very high levels. Although both walrus and bearded seals are Arctic endemic species that rely on sea ice for critical life history stages, and fill similar ecological niches, they clearly have different timing in their occupation of the CEO/Hanna Shoal region. This suggests that these Arctic pinnipeds may be partitioning this region of the Arctic based on the presence or absence of sea ice.

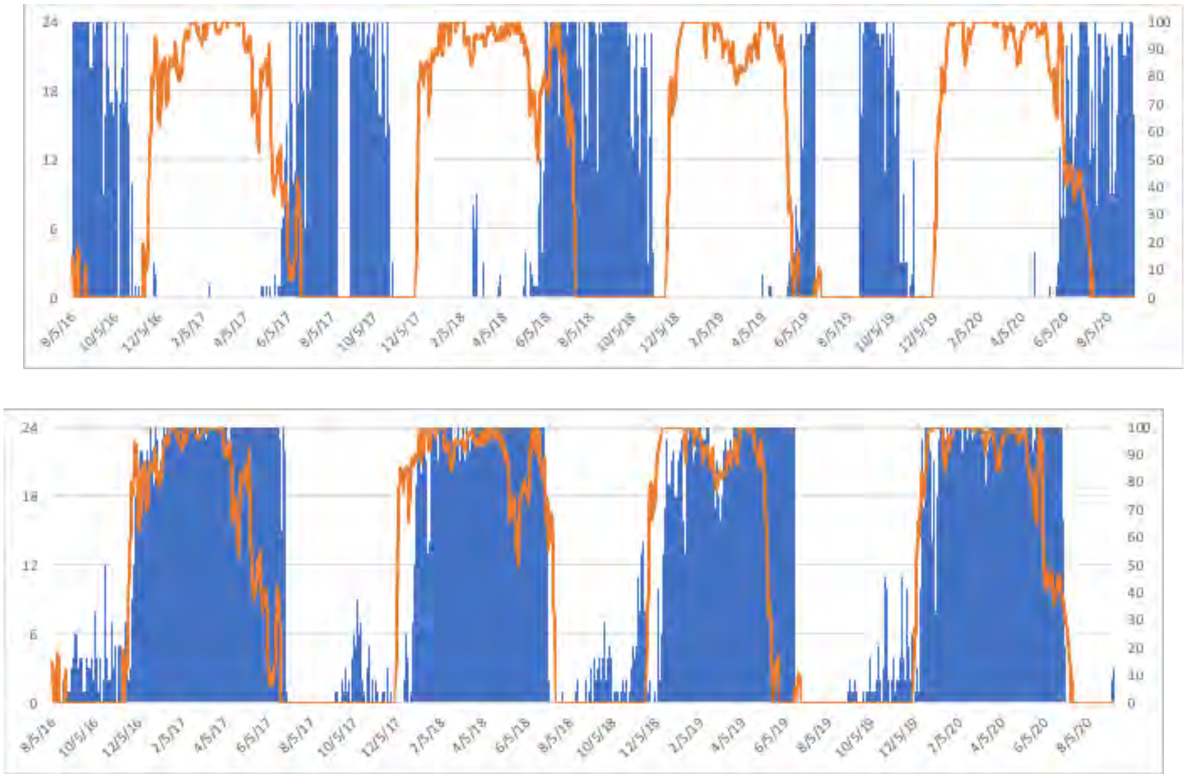

Figure 10. Acoustic detections of walrus (top panel) and bearded seals (bottom panel) with sea ice concentration (orange line) at the Chukchi Ecosystem Observatory from 2016-2020.

Chapter 5: Shipping noise in the Bering Strait

Relationship between vessel speed and sound levels in the Bering Strait

Escajeda, E., Stafford, K.M., R. Woodgate, K.L. Laidre. *In prep*

This chapter will form part of the PhD dissertation of Erica Escajeda at the University of Washington.

Vessel speed limits have been proposed as a means of reducing underwater ship noise, however it is unclear how effective such a measure would be in the Bering Strait, a natural bottleneck for ships transiting into the Arctic from the Pacific Ocean. In this study, we examine how ship noise varies with vessel type and speed using Automatic Identification System (AIS) data collected from vessels traveling through the strait along with acoustic recordings from three moored hydrophones. We matched recordings with ship noise to individual vessels that passed within 100 km of each hydrophone in June through November 2013–2015. A total of 67 sound files were analyzed, with tug (n = 21) and cargo ships (n = 16) as the most common vessel type observed in our dataset. Sound levels for each vessel were calculated and compared as a function of vessel type and speed. The results of our study could inform policymakers and managers on the effectiveness of vessel speed limits on reducing ship noise in a sensitive Arctic habitat.

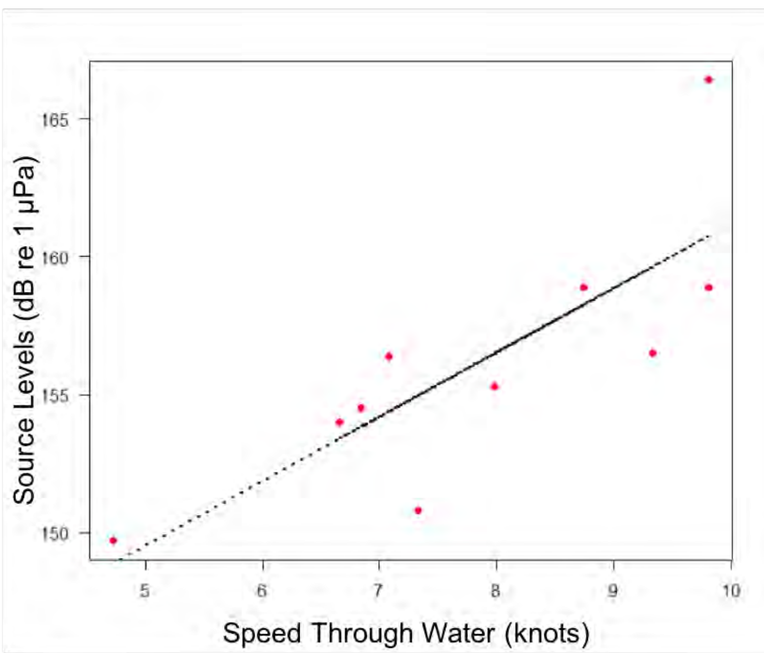

Figure 11. Relationship between source levels and speed through water for large (> 30 m)tugs under low (<10 m/s) wind speeds.

In the Arctic, the main sources of naturally occurring sounds include waves, winds, sea ice, and marine mammals. There is a direct correlation between increasing wind speeds and increasing ambient sound levels over open water. Sound levels tend to be higher for the same wind speed in shallow waters, such as those found in much of the nearshore Arctic, including the northern Bering and southern Chukchi Seas, than in deep waters. With increasing open water, not only is noise from wind and waves increasing but noise from large ships such as tankers, tugs, and fishing vessels may be increasing as they take advantage of the increasing open water season in the Arctic. The sounds from these vessels are relatively low frequency (< 1000 Hz) and in the same frequency band used by many Arctic species including bowhead whales, walrus, bearded, ringed and ribbon seals.

Vessel traffic through the Bering Strait increased 150% from 2008-2018 and the distance sailed in the Arctic Polar Code Area increased by 160% from 2013-2019 (PAME 2020). Vessels that passed through the Bering Strait from June to November in 2013-2015 included cargo ships, tankers, fishing vessels, research vessels, tugboats, passenger ships, and supply vessels. To determine the contribution of these ships to overall noise levels in the Bering Strait region, ship source levels were estimated and compared to vessel speed. If ship noise increases significantly with vessel speed, as has been shown elsewhere in the world, then speed limits might be an effective mitigation tool for limiting underwater noise from transiting vessels.

Chapter 6: Northward Range Expansion of Subarctic Upper Trophic Level Animals into the Pacific Arctic Region

Stafford, K.M.[1,2], E. Farley[3], M. Ferguson[4], K.J. Kuletz[5], R. Levine[6]. *In review.* Northward Range Expansion of Subarctic Upper Trophic Level Animals into the Pacific Arctic Region. Oceanography

Abstract

In the Arctic, studies of the impacts of climate change in marine ecosystems have largely centered on endemic species, ecosystems, and the people who rely on them. Fewer studies have focused on the northward expansion of upper trophic level (UTL) subarctic species. We provide an overview of changes in the temporal and spatial distributions of subarctic fish, birds, and cetaceans, with a focus on the Pacific Arctic Region. Increasing water temperatures throughout the Arctic have increased 'thermal habitat' for subarctic fish species, resulting in northward shifts of species including walleye pollock and pink salmon. Ecosystem changes are altering the community composition and species richness of seabirds in the Arctic, as water temperatures change the available prey field which dictates the presence of planktivorous versus piscivorous seabird species. Finally, subarctic whales, among them killer and humpback whales, are arriving earlier, staying later, and moving consistently farther north, as evidenced by aerial survey and acoustic detections. Increasing ice-free habitat and changes in water mass distributions in the Arctic are changing the underlying prey structure, drawing UTL species northwards, by increasing spatial and temporal habitat for them. A large-scale shuffling of subarctic and Arctic communities is reorganizing high-latitude marine ecosystems.

Introduction

Poleward range expansion of plant and animal species is one clear indication of climate change. Such distribution shifts in the ocean may be driven by changes in temperature, nutrients or, as in the Arctic and Antarctic, sea ice extent. These atmospherically-driven alterations are inextricably linked to changes in: wind-driven mixing or circulation affecting nutrient supply, greenhouse gases which trap heat, and subsurface and deep ocean heat driving sea ice declines (Tamarin-Brodsky and Kaspi, 2017; Woodgate and Peralta-Ferriz, 2021). Under new climate regimes, species whose life history strategies allow them to rapidly adapt or expand into novel habitat such as large, migratory generalist feeders, can become climate change 'winners' (Kortsch et al., 2015; Moore and Reeves, 2018). Subsequent impacts on endemic ecosystems will depend on resource availability and competition among species. As the climate continues to warm, temperate regions are becoming 'tropicalized' and Arctic regions are becoming 'borealized' with subarctic species increasing in abundance and expanding their range northward (Fossheim et al., 2015; Alabia et al., 2018; Polyakov et al., 2020).

While climate change is altering the entire Arctic, not every region is equally affected; the Arctic is highly heterogeneous (e.g. Moore et al., 2019; Polyakov et al., 2020; Mueter et al., 2021a). In the Atlantic, there are two wide, deep, high latitude, gateways to the Arctic: Davis Strait (300-900 km wide) and Fram Strait/Barents Sea (~450 km wide). The sole gateway to the Pacific Arctic is through the narrow Bering Strait (80 km), south of the broad, shallow Chukchi Sea shelf (Figure 1). Observed differences between the Atlantic and Pacific Arctic regions include a much greater increase in the open water season in the

Barents Sea than the Chukchi Sea, and differences in water mass composition and advection of heat and nutrients, all of which shape ecosystem structure (Hunt et al., 2013; Oziel et al., 2017).

Numerous recent studies have illustrated how changes in sea ice are potentially altering biological components of subarctic and Arctic marine ecosystems. Many of these studies have focused on the impacts of climate change on Arctic endemic species (Laidre et al., 2008; Divoky et al., 2021), ecosystems (Post et al. 2013, Grebmeier and Maslowski, 2014; Pecuchet et al., 2020), and the people who rely on them (Huntington et al., 2016; 2020; 2021). In particular, the inclusion of upper trophic level (UTL) taxa in the suite of measurements collected by the Distributed Biological Observatory has provided novel information on ecosystem dynamics at key locations across decadal time scales (Moore and Kuletz, 2019; Stafford et al., 2021). Several recent studies have also highlighted the role that UTL consumers such as marine fish, birds, and mammals can play as bellwethers of climate change and how understanding their abundance, distribution, and diet can aid in tracking ecosystem-level biological responses to rapid change (e.g. Moore et al., 2014; 2019; Sydeman et al., 2021).

Here we review recent information on northward range expansions of subarctic marine fish, seabirds, and mammals whose life histories have in some instances included limited seasonal occupation of the Arctic, with a focus on exemplar case studies from the Pacific Arctic Region. Our overarching goal is to provide a diverse audience with an updated overview of the observed recent changes in the spatial and temporal distributions of subarctic marine fishes, seabirds, and marine mammals, and to explain linkages among changes in the biology, atmosphere, oceans, and cryosphere.

Marine fishes

Marine fish species can rapidly track environmental change (Sorte et al., 2010; Pinsky et al., 2013). This is evident in the borealization of the Barents Sea in particular, where subarctic species including mackerel and Atlantic cod are expanding their range from the North Atlantic (Johannesen et al., 2012) while the distribution of Arctic species is retracting northward (Fossheim et al., 2015; Frainer et al., 2017). As the region continues to warm, the thermal habitat for boreal species has shifted farther into the Arctic (Eriksen et al., 2020), and generalist boreal fishes are likely to outcompete the specialist diets of Arctic species (Kortsch et al., 2015).

Sigler et al., (2011) examined fish distribution in the Pacific Arctic Region from the first decade of this century and found clear divisions in the distribution of planktivorous versus piscivorous species between the Bering Sea and the Chukchi and Beaufort seas as well as regional differences in taxa among bottom and surface fishes. Despite some evidence of northward migrations of subarctic species from the Bering Sea, those authors concluded that the persistence of the Bering Sea cold pool (Stabeno et al., 2001) would restrict range extensions of bottom fish such as walleye pollock, while pelagic species, such as pink salmon, might not be restricted by this thermal barrier (Sigler et al., 2011). However, given the retraction and possible collapse of the cold pool in recent years (Stabeno and Bell, 2019), more recent data suggest that these range extensions are long-term (Grüss et al., 2021).

Walleye pollock - Walleye pollock are widely distributed throughout the North Pacific, with known spawning grounds across the continental shelves from Japan to western Canada (Bailey et al., 1999). Cold bottom water in winter typically restricts the northward extent of the population. Adult pollock seasonally migrate northward and inshore in summer and return to the outer shelf to avoid the cold pool (Kotwicki et al., 2005). Reduced size of the cold pool lessens the barrier for adult pollock to remain on the inner and northern shelf throughout the year, resulting in a northward shift during recent warm conditions (Stevenson and Lauth, 2019; Eisner et al., 2020; Grüss et al., 2021).

North of the Bering Strait, the forage fish community in summer is dominated by small juvenile Arctic cod (De Robertis et al., 2017). Other common forage fishes in the region include capelin, and Pacific herring, both of which are observed nearshore and largely in the southern Chukchi Sea. Juvenile pollock had previously been found in very low densities with few adults present (Wyllie-Echeverria, 1995; Mecklenburg et al., 2007; Rand and Logerwell, 2011; Goddard et al., 2014). Surveys during the recent period of extreme warming (2017-2020) indicate that while the distributions of the other pelagic forage fishes have not significantly changed, pollock abundance in the Pacific Arctic has substantially increased (Figure 2). In the eastern Chukchi Sea, juvenile pollock were widespread and highly abundant in 2017 and 2019 and found in comparable densities to Arctic species (Levine et al., 2021; Levine et al., in review). In the Russian sector, surveys in 2018 and 2019 found a significant increase in both juvenile and adult pollock north of the Chukotka Peninsula (Orlov et al., 2019). It is hypothesized that the recent increase in adult pollock in the northern Bering Sea serves as a source population for the larval and juvenile population observed in the Chukchi and Beaufort seas (Levine et al., 2021), due to increased transport of Pacific water (Woodgate and Peralta-Ferriz, 2021) that advects juvenile fish northward.

Juvenile pollock growth rates exceed those of other gadid species under the warm conditions of the Arctic summer (Laurel et al., 2016), potentially allowing them to outcompete Arctic species; however, their hatch and survival rates are reduced under the seasonal freezing conditions (Laurel et al., 2018). Thus, while the substantial increase in juvenile pollock in the Pacific Arctic suggests that environmental conditions now allow pollock to extend into the Chukchi Sea on a seasonal basis, their ability to establish permanent populations in the Arctic remains unknown.

Pink salmon - Among salmonids, pink salmon are the most abundant species in the North Pacific Ocean (Ruggerone and Irvine, 2018) and have the broadest distribution in the Pacific Arctic Region. They occur from the large Yukon River to smaller coastal streams as far north as Point Barrow (Craig and Haldorson, 1986). Vagrants have also been found upstream in the Mackenzie River, extending eastward across the Beaufort Sea towards Amundsen Gulf, and along the east coast of Greenland (Dunmall et al., 2013; 2018). Spawning pink salmon have also been documented along the Chukotka Peninsula coastline from the northern Bering Sea into the Chukchi Sea and as far west as the Kolyma River (Radchenko et al., 2018). While pink salmon abundance in northern regions of their range is still quite low in relation to stocks farther south, there is evidence that the abundance of some northern stocks is increasing. For example, adult pink salmon have become more prevalent in subsistence catches in the high Arctic, particularly during even-numbered years (Dumnall et al., 2013; 2018). Furthermore, a survey during late summer 2007 found large numbers of juvenile pink salmon in the southern Chukchi Sea; these juveniles were larger and had higher energy content than juvenile pink salmon captured farther south (Moss et al., 2009). Consequently, adult pink salmon returns to the Beaufort Sea coast during 2008 were higher than in 2007 (Dunmall et al., 2013; 2018). It is still not clear whether the large catch of juvenile pink salmon in the Chukchi Sea in 2007 contributed to the higher returns in 2008. Conditions in both freshwater and marine environments are important to the survival of pink salmon (Farley et al., 2020). In the northern extent of pink salmon distribution, cold river and stream temperatures in the freshwater environment are believed to limit salmon production (Dunmall et al., 2016); however, continued warming of air and stream temperatures, and longer periods of ice-free conditions may benefit salmon survival in this environment (Nielson et al., 2013).

Seabirds

Seabirds link Arctic and subarctic marine and terrestrial ecosystems because they require land to nest and raise young but forage in the ocean. Globally, pelagic seabird occurrence and distributions reflect surface and subsurface zooplankton and forage fish upon which they feed (e.g. Sydeman et al., 2010). In the Pacific Arctic Region, seabirds have been associated with underwater features and water mass characteristics which aggregate their prey (Gall et al., 2013; Kuletz et al., 2015). During chick rearing, seabirds must find sufficient, high-quality prey within foraging distance of their nests, which can vary from a dozen to hundreds of kilometers, depending on species and reproductive phase. When not breeding, many species are capable of long-distance migrations covering thousands of kilometers.

Sea ice cover in the Arctic affects seabird foraging and extensive ice can restrict their access to prey. However, the marginal ice zone can provide a rich foraging opportunity (Hunt et al., 1996), as zooplankton and fish species often aggregate at ice edge habitats (Daase et al., 2021). Changes in sea ice extent and water temperature have resulted in changes in the available prey field for seabirds throughout the Arctic (Mallory et al., 2010; Frederiksen et al., 2013; Gall et al., 2017; Mueter et al., 2021a). For instance, in the North Atlantic, little auk wintering distribution expands and contracts with their subarctic copepod prey, which is shifting northwards (Amélineau et al., 2018). In the Pacific Arctic, low sea ice and warmer sea temperatures have been associated with low reproductive success and seabird die-offs, apparently due to low prey availability (Duffy-Anderson et al., 2019; Romano et al., 2020).

The timing of spring ice retreat in the Pacific Arctic has been shown to affect seabird distribution on the Bering Sea shelf, with contrasting patterns between birds that forage at the water's surface and species that are sub-surface foragers (Hunt et al., 2018). Early-spring sea ice retreat thus affects the spatial distribution of seabird species evident in summer and alters seabird communities. Ecosystem changes are clearly changing the community composition and species richness of seabirds in the Arctic (Descamps and Strøm, 2021; Mueter et al., 2021b).

Four decades of at-sea surveys (available in the North Pacific Pelagic Seabird Database; Drew and Piatt, 2015) have generally shown that decreased sea ice cover and higher ocean temperatures during the 2000s favored planktivorous seabirds over piscivorous seabirds in the Chukchi Sea (Gall et al., 2017). With further warming, some species have shifted their overall distributions northward, likely in search of food (Kuletz et al., 2020). During the relatively warm years of 2016-2019, Will et al. (2020) concluded that conditions were detrimental to planktivorous auklets nesting in the northern Bering Sea. Because warmer ocean temperatures have been linked to the replacement of larger, lipid-rich zooplankton species with smaller, lipid-poor species (Eisner et al., 2013), on-going changes in the Pacific Arctic may no longer favor planktivorous seabirds.

In the Bering Sea, subarctic seabirds that appear to be expanding their post-breeding dispersal ranges northwards include three species of Pacific albatrosses (Kuletz et al., 2014), northern fulmars (Renner et al., 2013), and ancient murrelets (Day et al., 2013). For all seabirds combined, there was a shift in distribution farther into the Pacific Arctic during the warm years of 2017-2019, compared to the previous decade (Figure 3). This northward shift included birds that breed in the Bering and Chukchi seas (e.g., thick-billed murre), migrants that breed in the southern hemisphere but come to Alaska during their non-breeding season (e.g., short-tailed shearwater) (Kuletz et al., 2020), and Atlantic species that might have crossed the Canadian Arctic Archipelago (e.g., northern gannet; Day et al., 2013). Based on data from the eastern Chukchi Sea, seabirds that had been spatially correlated with prey communities during a relatively cool year (2015) were decoupled from the same communities in a warm year (2017), suggesting that these seabird communities did not adapt, at least in the short term, to a rapid change in conditions (Mueter et al., 2021b).

Cetaceans

Marine mammals have exhibited phenological and distributional changes throughout the Arctic. Endemic Arctic marine mammals spend their lives in the Arctic, often closely associated with sea ice. A number of subarctic species, particularly cetaceans, have become regular summer and autumn visitors to the Arctic, migrating into the region as sea ice melts in the spring or early summer and out of the region as the sea surface freezes in late autumn or early winter (Hamilton et al., 2021). As sea ice has declined in age, thickness, and extent throughout the Arctic, prey distributions have shifted and new migratory corridors have opened for subarctic marine mammal species (Buchholz et al., 2012; Berge et al., 2015; Storrie et al., 2018). These changes have expanded the temporal and spatial boundaries of habitat for cetaceans: they are now arriving in the Arctic earlier, staying later, and migrating farther north (Nieukirk et al., 2020; Ahonen et al., 2021).

Killer whales - Killer whales are a globally distributed top predator with ecotypes that are distinguished by their phenotypes and preferred prey (de Bruyn et al., 2013). Killer whales are not a new species in the Arctic as they have been documented there sporadically in summer months, feeding on a variety of marine mammal species (Stafford, 2019; LeFort et al., 2020). In the Arctic, killer whales avoid dense ice, and heavy multi-year sea ice once excluded them from most high Arctic regions during many months of the year; whales still avoid heavy sea ice (Matthews et al., 2011). Their increasing occurrence in the Arctic as sea ice declines, in thickness and extent, represents seasonal and geographic expansion. Recent (2010-present) sighting and passive acoustic monitoring data provide evidence that this species is arriving in the Arctic earlier, departing later, and moving farther north in the eastern Canadian Arctic and north and east in the Pacific Arctic (Higdon and Ferguson, 2009; Ferguson et al., 2010; Stafford, 2019; Figure 4). In the Pacific Arctic, passive acoustic monitoring has recently documented killer whales throughout the Chukchi Sea as far north as 75° N (Stafford et al., in review). This species has been heard in the Pacific Arctic as early as May and as late as October (Stafford, 2019). In both the Canadian and Pacific Arctic, the number of bowhead whales with killer whale scars has increased over time (Reinhard et al., 2013; George et al., 2017) as has evidence from bowhead whale carcasses of depredation (Willoughby et al., 2020). Matthews et al. (2019) posit that periodic ice entrapments of killer whales, which are usually fatal (Westdal et al., 2016), may slow their expansion into the Arctic, particularly as naïve whales explore regions that can be ice choke points.

The northward range expansion, longer seasonal presence, and higher numbers of a top predator into the Arctic has the potential for top-down ecosystem reorganization and may represent the most immediate threat to Arctic endemic species (Ferguson et al., 2010). In the eastern Canadian Arctic, endemic narwhals, belugas, and bowhead whales change their behavior in the presence of killer whales (reviewed in Matthews et al., 2020). Lefort et al. (2020) suggest that this species could have a significant negative impact on narwhal populations in the Canadian Arctic Archipelago.

Subarctic Baleen whales - The historical occurrence of humpback, fin, and minke whales north of Bering Strait was documented by Soviet scientists, particularly near the Chukotka Peninsula, from June to October (summarized in Clarke et al., 2013). These species are regularly found in the Bering Sea during summer (Ferguson et al., 2015) and fin whales are present there year-round (Stafford et al., 2010). Evidence from visual (shipboard and aerial) and acoustic monitoring suggest that their use of the Pacific Arctic may be increasing (Clarke et al., 2013; 2020; Brower et al., 2018).

Four decades of aerial surveys (Clarke et al., 2020) have provided the most extensive information on subarctic whales in the US Pacific Arctic. Fin whales first appeared north of Bering Strait in the aerial survey database in 2008, humpback whales in 2009, and minke whales in 2011. All three subarctic baleen whales were sighted in every month from July through October, although most of the sightings through 2019 occurred from July through September (Clarke et al., 2020). Furthermore, fin and humpback whale calves have been observed in the region (Clarke et al., 2020). Aerial survey observers commonly recorded all three species in close proximity to each other and to gray whales, particularly in Hope Basin, a benthic hotspot in the southcentral Chukchi Sea (Clarke et al., 2020). In 2019, the number of subarctic baleen whales detected per kilometer surveyed over Herald Shoal, which is ~145 km northwest of Point Lay, was 12.5 times greater than in any previous survey year. All three species have been documented feeding in the Pacific Arctic Region, and it is likely that the northward expansion of prey (krill and forage fish/or small schooling fish) distributions provided the whales' motivation to migrate to the Pacific Arctic (Clarke et al., 2020).

Concluding thoughts

What does the future hold for upper trophic level species and communities in the Arctic? It is clear across taxa that the effects of climate change are variable and dependent on the different ecological requirements of communities, feeding guilds, species, and age classes. There is no indication that climate change in the Arctic is going to decelerate any time soon. The habitat changes that have been seen in the past two decades will become the 'new normal' (Thoman et al., 2020). There is clear evidence of temporal-spatial range expansion for many subarctic UTL species. Increasing ice-free habitat and changes in water mass distributions are changing the underlying prey structure and therefore attracting new UTL species, increasing habitat extent, and/or increasing the duration of residency in Arctic habitats. But for many subarctic species, annual sea ice cover, freezing temperatures, and months of darkness may still prevent them from becoming true Arctic residents. Pollock eggs and larvae are highly sensitive to cold temperatures, central place foraging seabirds need adequate nesting habitat within foraging distance of high prey abundance, and subarctic cetaceans can still be excluded from heavy ice as they risk injury to their dorsal fins and entrapment from ice. To permanently expand northwards, UTL species require the flexibility in physiology and behavior to adapt to on-going habitat perturbations. If new species can adapt to year-round life in the Arctic, understanding the risks to Arctic endemic species from competition for prey, novel predators, and exposure to novel pathogens will be critical (e.g. Post et al., 2013; Kortsch et al., 2015; VanWormer et al., 2019). The evidence we summarize here indicate large-scale shuffling of subarctic and Arctic marine animal communities as high-latitude marine ecosystems undergo rapid reorganization.

Acknowledgments

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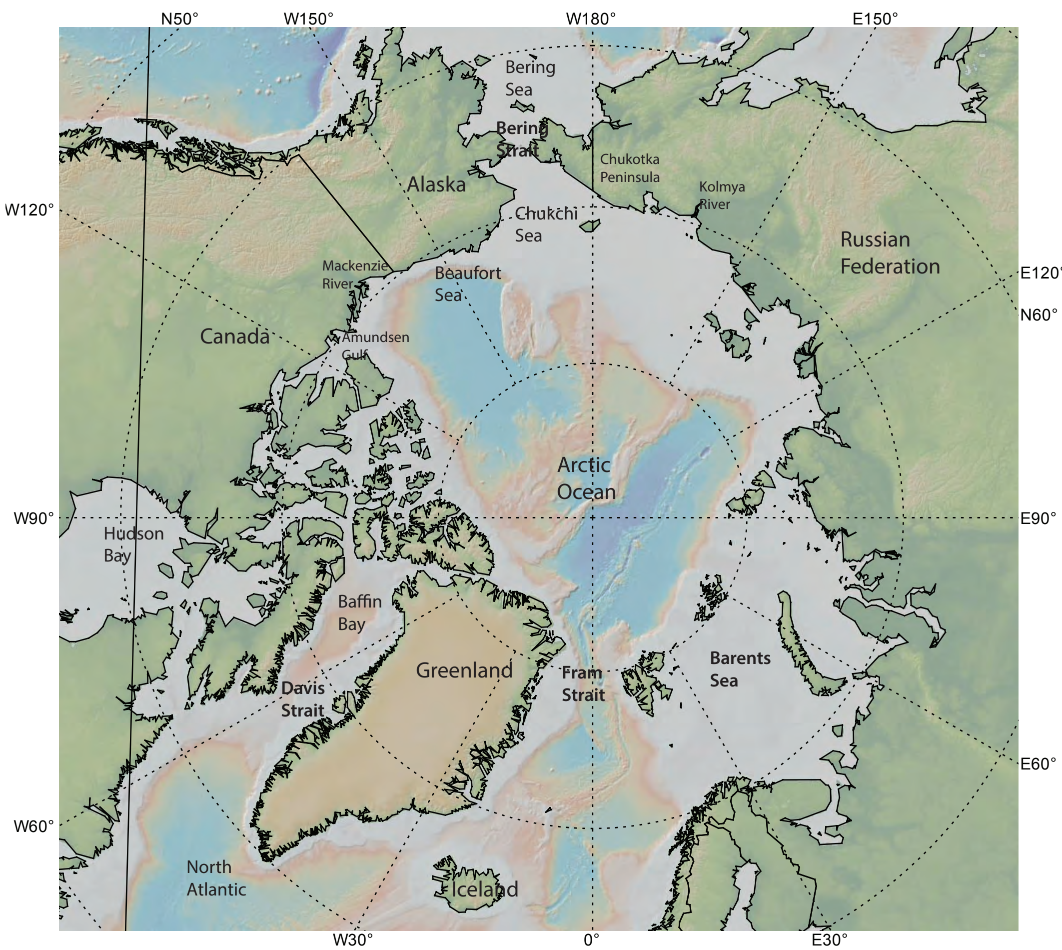


Figure 12. Map of the Arctic showing major gateways and waterways. Figure made with GeoMapApp (www.geomapapp.org) / (Ryan et al., 2009).

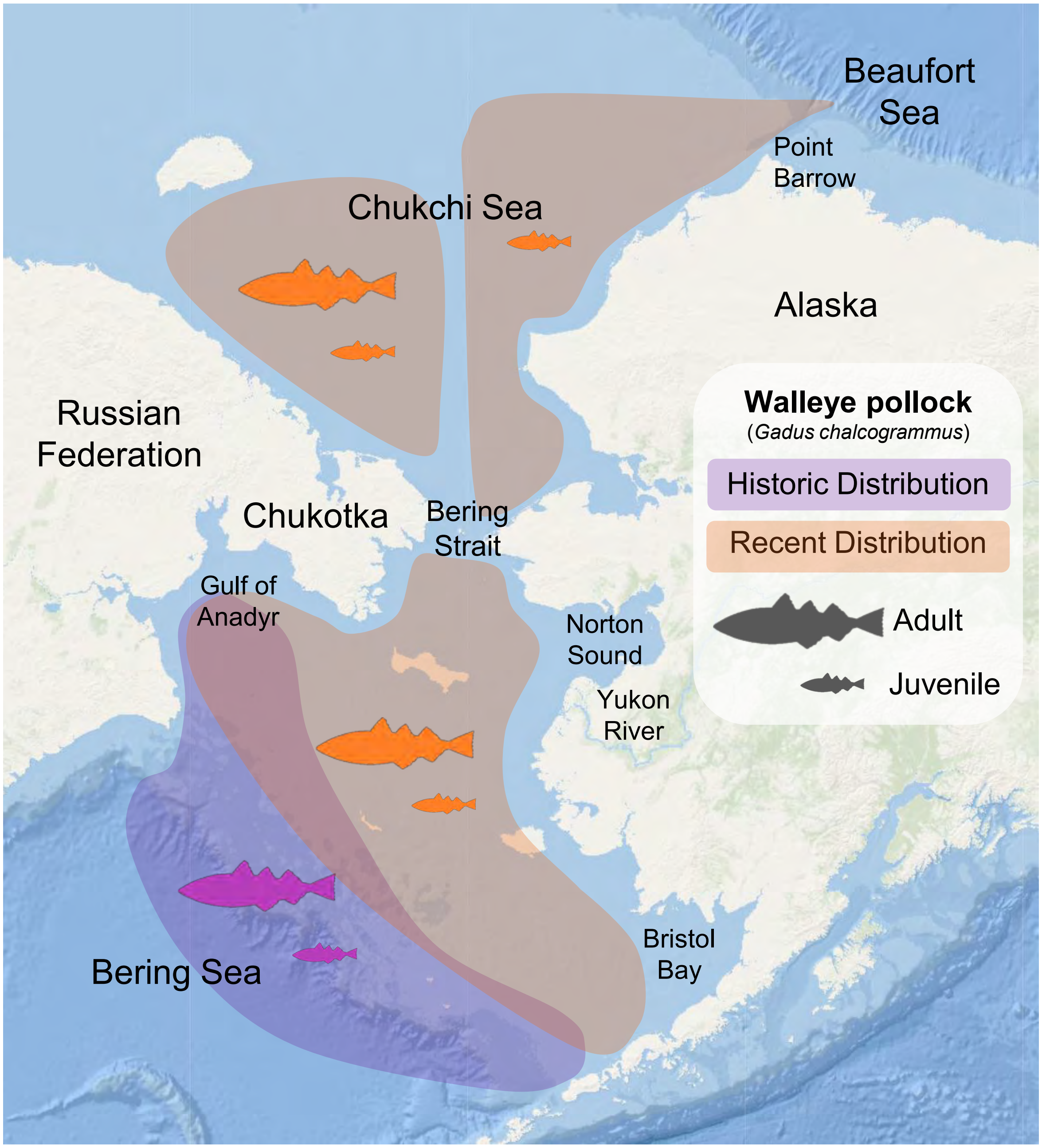


Figure 13. Historic and recent observations of walleye pollock distributions in the Bering and Chukchi Seas. Recent warming has led to a northward shift of the population in the Bering Sea (approximate distributions from Eisner et al., 2020), and surveys have reported large pollock populations in the eastern (juvenile only, Levine et al., in review) and western (adult and juvenile, Orlov et al., 2019) Chukchi Sea.

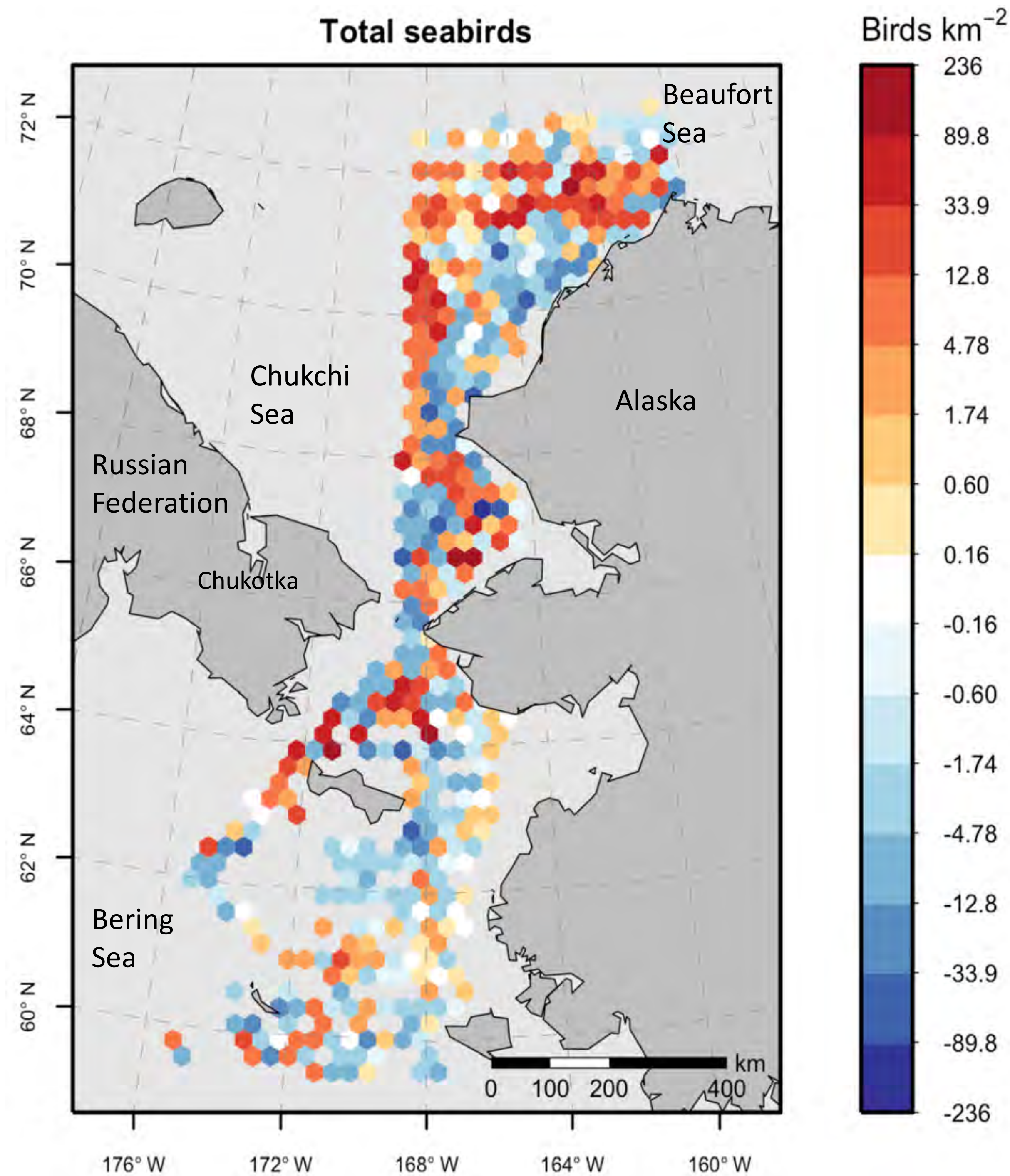


Figure 14. Distribution changes in the Pacific Arctic Region for total seabird densities (birds km-2) during 2017-2019, compared to the previous decade. Cells with higher densities in the latter years (blues) and lower densities (oranges) were based on mean densities of all observations within each 50-km grid cell. (Adapted from Kuletz et al., 2020).

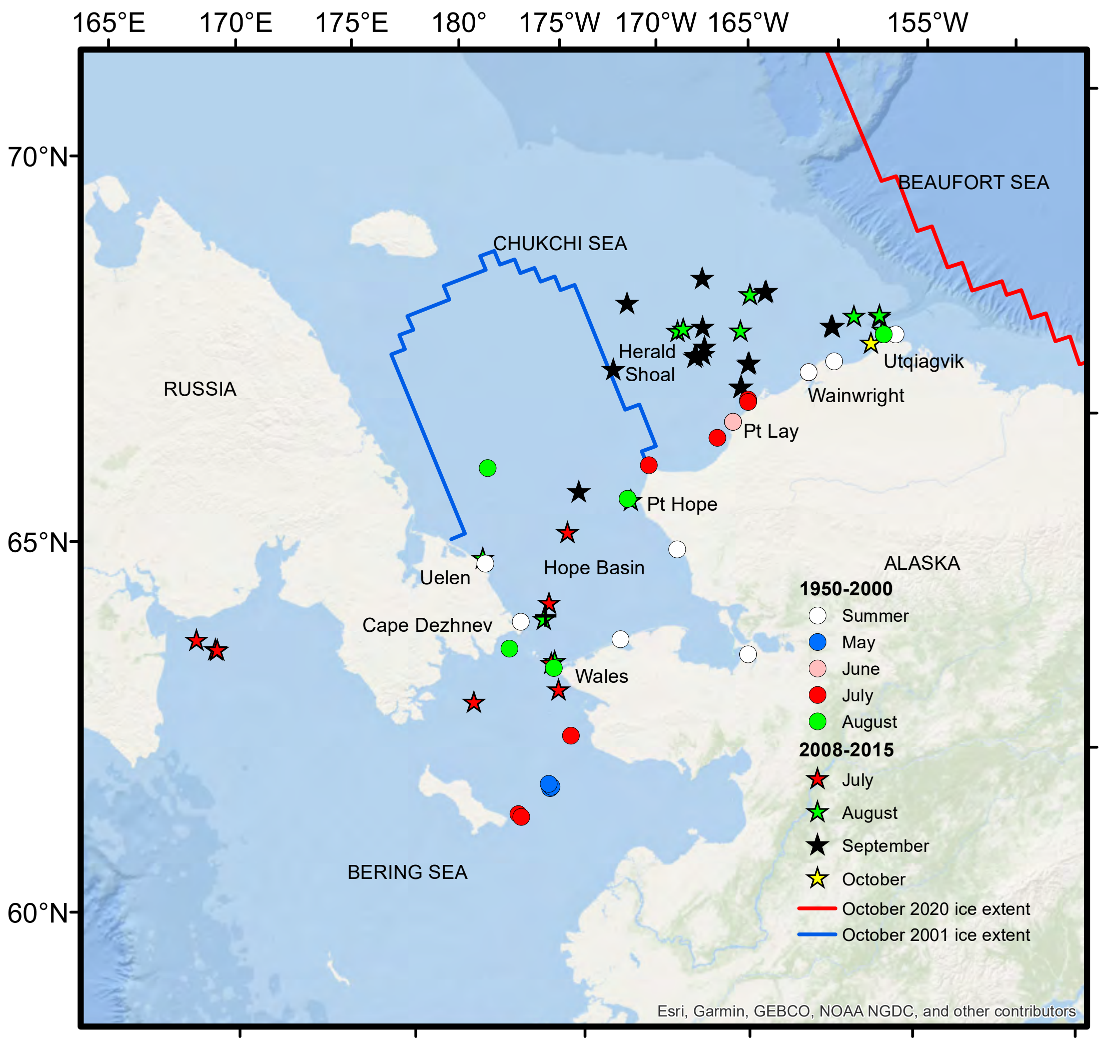


Figure 15. Killer whale sightings in the Pacific Arctic by month from 1950-2000 (circles) and 2008-2019 (stars)(Adapted from Stafford 2019). Sea ice extent is shown for October 2001(blue) and 2020 (red).

Chapter 7: Evidence suggests potential transformation of the Pacific Arctic Ecosystem is underway

Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M Stafford, D. Stockwell and C. Wilson, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, 10(4), pp.342-348

Abstract

The highly productive northern Bering and Chukchi marine shelf ecosystem has long been dominated by strong seasonality in sea ice and water temperatures. Extremely warm conditions from 2017 into 2019 – including loss of ice cover across portions of the region in all three winters – were a marked change even from other recent warm years. Biological indicators suggest this state change could alter ecosystem structure and function. Here we report observations of key physical drivers, biological responses, and consequences for humans, including subsistence hunting, commercial fishing, and industrial shipping.

We consider whether observed state changes are indicative of future norms, whether an ecosystem transformation is already underway, and if so, whether shifts are synchronously functional and system-wide, or reveal a slower cascade of changes from the physical environment through the food web to human society. Understanding of this observed process of ecosystem reorganization may shed light on transformations occurring elsewhere.

General Discussion

Environmental Setting

The Arctic IERP proposals were written in 2016, in the midst of the well-documented North Pacific Marine Heatwave (refs; Walsh et al, 2018). Although "the Blob" of warm water was first identified in the Gulf of Alaska (Freeland et al., 2014; Bond et al., 2015) and many dramatic examples of Gulf of Alaska ecosystem impacts were evident at that time and documented in the years since (Piatt et al., 2018, Suryan et al, 2021), anomalous warmth also extended across the Pacific Arctic at this time (Danielson et al., 2020). Little did we know, however, that the northern Bering and Chukchi seas were about to enter a period of unprecedented winter sea ice loss (Stabeno and Bell, 2018; Thoman et al., 2020) and equally as anomalous distribution shifts and changes in abundance of target commercial, non-commercial and subsistence harvest fishes and invertebrates as well as marine mammals (Huntington et al, 2020, Stevenson and Lauth, 2019).

Analysis of a nearly 100-year-long historical record (Danielson et al. 2020) shows that the Bering and Chukchi continental shelves exhibit different trends and multi-year intervals of warm and cold conditions – suggesting that while the Chukchi receives input from the Bering Sea it operates somewhat independently of the Bering's upstream heat inputs: more local processes dominate. Analyses show that the heat engines of both shelves accelerated over 2014-2018, with increased surface heat flux exchanges and increased lateral oceanic heat advection.

In retrospect, it appears that the Arctic IERP field years (2017-2019) encompassed the peak of the thermally anomalous conditions in this particular multi-year phase of regionally warm conditions; they are the only three years in the record with annual mean monthly temperature anomalies of greater than 1.5 °C (Figure 25). Given the likelihood of continued future warming, these years likely represent a preview of what may eventually be considered typical.

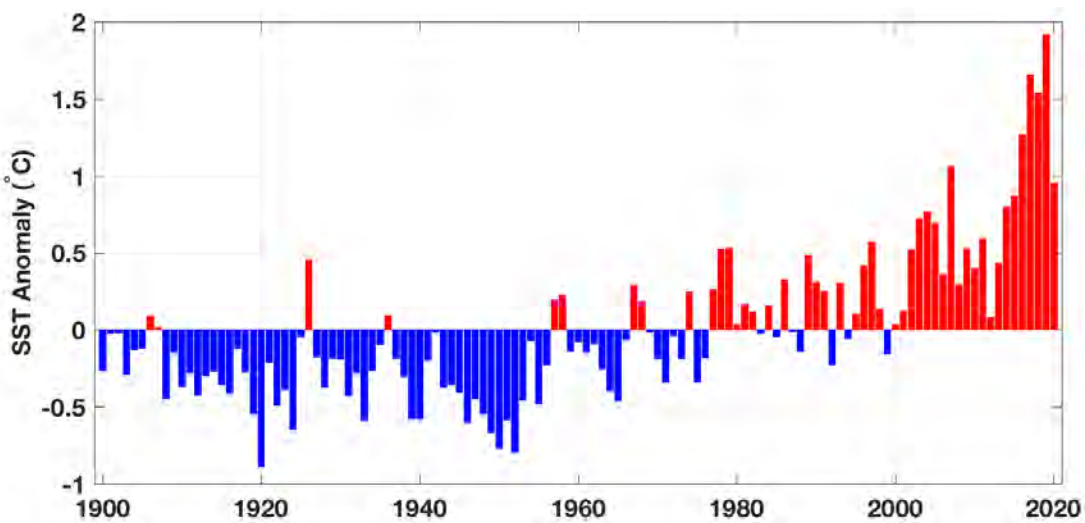


Figure 16. Sea surface temperature (SST) annual mean of all monthly anomalies over 1900-2020 from the Version 5 Extended Reconstructed SST dataset (ERSSTv5). Anomalies are computed relative to the full duration of this 1990-2020 time series. The integration region region for the data shown here extends across the whole of the Northern Bering and Chukchi Seas (60-75 °N, 180-155 °W).

The Over-arching Question

What regulates variations in carbon transfer pathways and how will the changing ice environment alter these pathways and ecosystem structure in the Pacific Arctic and beyond? How will a changing environment impact upper trophic level species and human use of the Arctic? Our observations and experiments revealed numerous insights into the character of the bottom-up forcing that helps maintain the Pacific Arctic shelf ecosystem, into how energy (carbon) is routed amongst the various marine system components from microbes to whales, and into how it may change in a warming climate. Temperature clearly stands out as a key factor in the regulation of energy consumption and trophic transfers, but temperature alone is far from the whole answer. The aggregate combination of species abundance and distributions and environmental setting (geomorphology of the Pacific Arctic shelves, large-scale pressure gradients driving mean flows, nutrient supply, strong seasonality in light, ice, winds) combined with the ability of the Pacific Arctic ecosystem to maintain its many services ultimately sets this ecosystem's unique biological character. While this character has never been static in nature, it appears to be crossing thresholds into states that have not previously been observed (Huntington et al., 2020).

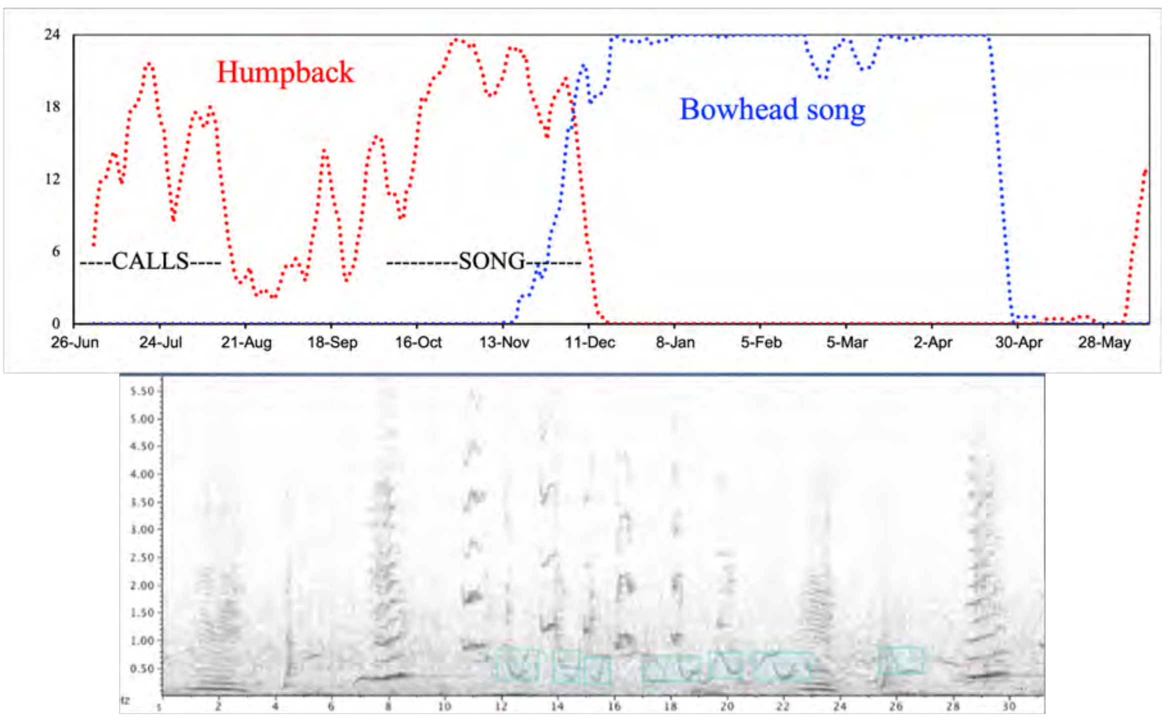


Figure 17. Seasonal occurrence of humpback and bowhead whale songs shows overlap in time and space in Anadyr Strait. In the spectrogram blue boxes highlight bowhead whale song notes in the midst of a humpback whale singing in late November 2017.

Extremely warm conditions from 2017 into 2019 – including loss of ice cover across portions of the region in all three winters – were a marked change even from other recent warm years and may represent a proxy for future decade "normal" conditions. Temperature-controlled respirometry experiments show that benthic oxygen consumption increases significantly (~30%) with warming temperatures and our mooring measurements showed an extended duration of time that the seafloor water temperatures remained 2-6 degrees above the freezing point during these recent warm years. Biological indicators, such as these temperature-dependent benthic respiration rates, suggest that thermal state change exhibits potential to alter ecosystem structure and function (Jones et al., 2021), but our measurements also show that the system exhibits resilient capacity to buffer some of the changes from a bottom-up perspective.

While the environmental alterations represent a bottom-up forcing, recent upper trophic level observations (Stevenson, D.E., Lauth, R.R., 2019; Huntington et. al. 2020, Stafford et al. Chapter 6) suggest that top-down forcing of the ecosystem will also play a key, and possibly dominant, role in determining future changes to the overall character of the Pacific Arctic ecosystem. For example, the influx of sub-Arctic Pacific Cod and Walleye Pollock exhibit potential to impart a more substantive impact on the benthic community than changes in benthic productivity due to altered pelagic realm export. Sensitivity of the local upper trophic level populations to anthropogenic disturbance (e.g. shipping traffic, noise) and intra-species competition represent other potential vulnerabilities.

In aggregate, our results have helped both define and constrain our understanding of the conditions in which the future warmer Pacific Arctic ecosystem will exist. The examples summarized here, and many others in the published manuscripts cited and reprinted in this report, directly contribute to our understanding of how energy in the marine ecosystem is routed now, and how it may change as the duration of sea ice cover continues to decline. The results of the ASGARD experiments will continue to be analyzed, synthesized, and published in coming years, each further revealing partial answers to the ASGARD and Arctic IERP over-arching question.

Application to Resource Management and Alaska Communities

Coastal Community Concerns

Food security is a paramount concern to residents of coastal communities that depend on a subsistence-based economy. Environmental conditions are changing rapidly and hunters find themselves dealing with a multitude of factors that can degrade hunt success (Fall et al., 2013). For example, hunters report that their ability to forecast the weather is now at times diminished, fuel costs are high; ice conditions are different and less safe, and game can be less accessible. Hunters are concerned with the impact of vessel traffic on the behavior and location of marine mammals, bycatch from commercial fisheries, and increasing rates of coastal erosion that threaten the placement of entire villages.

Practical applications of our research will directly address issues, questions and concerns posed by coastal community members (e.g., Huntington et al, 2021). These include: sea ice conditions and timing; whale, seal and walrus distributions with respect to vessel traffic noises; ramifications of changing climate conditions to the presence and success of marine mammals, clams, crabs, fish, and other animals; and toxic algae blooms that may impact whales and other marine mammals.

In particular, our research allows us to provide scientific lenses through which we can help interpret the causes and consequences of environmental change. As communities continue to adapt – as they have done for millennia – information from scientific studies and scientific observations can help inform community decisions. Such decisions now commonly deal with the practical aspects of addressing climate change impacts to the environment or location availability of subsistence food resources.

Shifting Norms: Management Implications

Perhaps even sooner than many had anticipated, state and federal agencies are confronting resource management issues tied to loss of sea ice and northward-shifting distributions of sub-Arctic marine species. The incursion of Pollock and Pacific Cod into the Bering Strait region – and farther north – demand consideration and a careful assessment of new management actions. Considerations need to include biodiversity, ecosystem structure, and ecosystem function in relation to any potential fishery harvest levels. The recent (since the start of the Arctic IERP) increase of commercial fishing in the Chukchi Sea waters of the Russian Federation suggests that despite insufficient data from the US side of the convention line in the Chukchi Sea, there likely exists significant quantities of Pollock and Pacific Cod on the US side as well. In US waters, any potential fishing activities must consider the cultures and subsistence lifestyles of local indigenous communities, potential impacts of industrial activities (e.g. commercial fishing, oil and gas extraction), potential changes to regional ocean carrying capacity, and resilience of the arctic marine ecosystem (NRC, 2014). An ecosystem-based approach to fisheries management necessitates consideration of food security of the coastal Indigenous communities, their traditional subsistence hunting activities, and conservation of endangered marine mammal and seabird species.

With carbon (or sometimes nitrogen) as the basic currency with which we describe and quantify biological and biophysical interactions - including growth, respiration, energy conversion, energy movement, energy storage and intra-trophic transfers - we need to understand the rate at which carbon is consumed, converted, stored, buried, and relocated. Biophysical numerical models require as inputs sinking rates, growth rates and respiration rates for all important species or functional groups (Stock et al., 2013). As outputs, models predict primary productivity, secondary productivity and biomass. ASGARD data provide spatially-explicit measures of the production and respiration rates for the dominant pelagic and benthic species, along with more basic information about composition, biomass and abundance. Such data will prove critical for advancing spatially and temporally explicit models of ecosystem structure and applying them in appropriate and statistically robust to future scenario projections.

Directions for Future Research

Following a concentrated effort of field work, analysis and publication, further advancements in scientific understanding relies on testable hypotheses and experimental designs that probe the edges of our knowledge base and place our findings into a more complete ecological context. The process of analysis and interpretation of the Arctic IERP results is still ongoing, but a number of future research needs are already apparent. Below, we list a series of specific research directions that are applicable to the entire ASGARD suite of measurements but are targeted to marine mammal and underwater noise data that could further improve our ability to dig deeper into the ASGARD and Arctic IERP guiding questions and could provide management agencies with actionable guidance.

Below, we identify seven study focal areas that would, if addressed, lead to a fuller understanding of the Pacific Arctic ecosystem, its drivers, and future trajectory. All of the below listed studies would fill information gaps and/or needs that resource management agencies could apply to their task mandates.

Ecosystem Status and Change

1. Comparison of ASGARD data to more typical years

Our campaign existed across the two warmest years on record for the study region and are thus not well characteristic of typical conditions found in the first two decades of the 21st century. Repeated measurements in more "normal" years would allow us to better assess our warm phase June month shipboard measurements and year-round mooring measurements.

2. Applying ASGARD measurements to ecosystem models

The ASGARD project was designed in part to provide data useful for the parameterization and/or validation of numerical models. The need for such modeling efforts has not diminished and we now have significant amounts of data that can help bring model studies to a more advanced stage of operation.

3. Non-summer observations

The ASGARD expeditions in June provided valuable data outside of the more typical sampling months of July-September, but seasonal coverage in sampling remains heavily biased to summer and early fall months. Shipboard biological sampling in late fall, winter and early spring could provide data that are important to our understanding during the dark and cold portion of the year. Ecosystem ramification of multiple stressors in the Pacific Arctic Warming, ocean acidification, hypoxia, and increasing vessel traffic and other anthropogenic impacts present the likelihood of unanticipated outcomes due to the nature of nonlinear coupling between multiple stressors. Our ability to assess future ecosystem conditions in the study region depends on improvements in our understanding of how the system as a whole responds to such factors.

4. Management of vessel locations and speeds in the Pacific Arctic region

Increasing vessel traffic poses a risk to protected marine mammal and seabird species. Modeling that assesses potential dynamic and/or adaptive management approaches would improve conservation efforts and reduce the potential for conflict. This need applies year-round due to the different migration timings of the various species of interest, and the fact that vessels are now transiting through the Bering Strait region in all months.

5. **Tracking of sub-Arctic species distribution, abundance, and biodiversity**

Sub-Arctic species range distributions have been increasing northward in recent decades, and more recent indications show potential for displacement of endemic Arctic species as ranges over

6. **Changing phenologies**

As the ice, temperature and light conditions change, the timing of species presence, absence, match-mismatch timing with food resources, migration considerations and human interactions all should be assessed with respect to animal behaviors and environmental conditions.

7. **Combined US and Russian sector studies**

Many data collections end at the international dateline, but the ecosystem is not bound by national boundaries. Studies that bridge both the US and Russian Federation sectors of the Bering and Chukchi seas are needed to gain holistic understanding of the system.

Publications, Presentations, Outreach, and Collaborations

The full ASGARD *Publications* is given in Danielson et al. ASGARD Final Report. Here we include only cruise reports, the passive acoustic and marine mammal ASGARD publications to date, publications in preparation, and other publications that utilize ASGARD data or the participation of the ASGARD marine mammal PI.

Publications

1. Arctic IERP, 2021. Arctic Integrated Ecosystem Research Program Final Summary Brochure, NPRB, Anchorage, AK.
2. Baker, M.R., Farley, E.V., Ladd, C., Danielson, S.L., Stafford, K.M., Huntington, H.P. and Dickson, D.M., 2020. Integrated ecosystem research in the Pacific Arctic–understanding ecosystem processes, timing and change. Deep-Sea Res. II, 177 (2020), p. 104850, https://doi.org/10.1016/j.dsr2.2021.104950
3. Danielson, S., O. Ahkings, L. Edenfeld, L. Eisner, C. Forster, S. Hardy, S. Hartz, B. Holladay, R. Hopcroft, B. Jones, J. Krause, K. Kuletz, R. Lekanoff, M. Lomas, K. Lu, B. Norcross, S. O'Daly, J. Pretty, C. Pham, A. Poje, E. Roth, S. Seabrook, P. Shipton, B. Smith, C. Smoot, K. Stafford, D. Stockwell, A. Yamaguchi, and A. Zinkann, 2017. SKQ2017-09S ASGARD Cruise Report. Fairbanks, AK
4. Escajeda, E, Stafford KM, Laidre KL, Woodgate R. in prep. Characterizing spatio-temporal patterns in the acoustic presence of subarctic baleen whales in the Bering Strait in relation to environmental factors
5. Escajeda, E, Stafford KM, Laidre KL, Woodgate R. Relationship between vessel speed and sound levels in the Bering Strait
6. Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M Stafford, D. Stockwell and C. Wilson, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, 10(4), pp.342-348
7. Moore SE, Clarke JT, Okkonen SR, Gerbmeier JM, Berchok CL, Stafford KM. *In review.* Changes in gray whale phenology and distribution related to prey variability and ocean biophysics in the northern Bering and eastern Chukchi seas. PLoSONE
8. Stafford KM, Farley E, Ferguson M, Kuletz K, Levine R. *Accepted*. Northward Range Expansion of Subarctic Upper Trophic Level Animals into the Pacific Arctic Region. Oceanography
9. Stafford KM and Danielson S. *In prep*. Seasonal and geographic variation of marine mammals in the northern Bering Sea
10. Stafford, K.M., Danielson, S.L., Escajeda, E., in prep. Long-term marine mammal occurrence at the Chukchi Ecosystem Observatory

Research Cruise Collaborations: Participant Home Institutions

- BIGELOW LABS FOR OCEAN SCIENCE
- BOEM

- DAUPHIN ISLAND SEA LAB
- HOKKAIDO UNIVERSITY
- NATIVE VILLAGE OF DIOMEDE
- NOAA-PMEL
- NPRB
- OSU
- UAF
- USFWS
- UW

Data Sharing and Publication Collaborations: Home Institutions

Alaska Center for Climate Assessment and Policy

- Alaska Department of Fish and Game
- Amundsen Science
- Institute of Ocean Sciences, Fisheries and Oceans Canada (IOS-DFO) Canada
- College of Earth, Ocean and Atmospheric Science, Oregon State University
- Florida State University Coastal and Marine Laboratory
- Huntington Consulting
- International Arctic Research Center and College of Natural Science and Mathematics
- Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan
- Native Village of Diomede
- NOAA, Alaska Fisheries Science Center, Auke Bay Lab
- NOAA, Alaska Fisheries Science Center, National Marine Fisheries Service
- NOAA, Pacific Marine Environmental Laboratory
- North Carolina State University
- North Slope Borough Department of Wildlife Management
- Russian Federal Research Institute of Fisheries and Oceanography, Pacific Branch of VINRO, TINRO, Vladivostok, Russia
- Stantec
- University of Toronto Mississauga, Mississauga, ON, Canada
- University of Manitoba, Winnipeg, Manitoba, Canada
- University of Maryland Center for Environmental Sciences, Chesapeake Biological Laboratory
- University of Washington, Applied Physics Laboratory
- University of Washington, Joint Institute for the Study of the Atmosphere and Ocean
- US Fish and Wildlife Service
- Woods Hole Oceanographic Institute

Sample Collections, Lab Analyses and Other Collaborations

(Including intra-Arctic IERP collaborations such as the NOAA-led Arctic EIS projects)

- Alaska Ocean Observing System (AOOS) (CEO program support)
- Alaska Sea Grant (UAF Nome Campus cruise support and community liaison support)
- Arctic Marine Biodiversity Observation Network (AMBON) (US Arctic biodiversity)
- Bering Strait Mooring Program (APL-UW) (monitoring of Bering Strait)

- Chukchi Ecosystem Observatory (CEO) (NE Chukchi Mooring Site)
- Distributed Biological Observatory (DBO) (Bering-Chukchi-Beaufort change detect array)
- UAF Museum of the North (underwater acoustic samples as part of the new bowhead whale skeleton exhibit)
- University of Washington, Applied Physics Laboratory (mooring platform)
- Woods Hole Oceanographic Institution and UAF (glider support)

National and International Symposia Collaborations

- 2016 – present (1-2 times per year). ASGARD representation at Distributed Biological Observatory (DBO) and the Pacific Arctic Group (PAG) collaboration meetings.
- February 2018. AGU/ALSO Ocean Sciences Meeting. Scientific session organization (with DBO and AMBON) and participation: "Linkages Between Environmental Drivers and Structure of Arctic Ecosystems". Session Abstract: Arctic ecosystems are adjusting to rapidly warming temperatures, sea ice loss and a myriad of other factors that are changing with time. Temperature-growth relations, altered seasonality, expanded and contracted range extents, and new trophic pathways may each affect biodiversity, population status of key species, and relations between humans and marine resources. As environmental change continues, can we anticipate how future Arctic ecosystems will compare to those of yesterday and today? Will the effects of a changing climate be the same across various Arctic regions? We welcome presentations from all regions of the Arctic examining rates, processes and mechanistic controls that impart structure on any aspect of the high-latitude marine ecosystem.
- February 2020. AGU/ALSO Ocean Sciences Meeting. Scientific session organization (with DBO and AMBON) and participation: "Ecosystem Structure in a Changing Arctic". Session Abstract: The rate of atmospheric warming in the Arctic is outpacing that of other regions, and is associated with sea ice loss, warming ocean temperatures, changes in the hydrological cycle, and impacted ecosystems. Temperature-growth relations, nutrient cycling dynamics, altered seasonality, changing freshwater balances, expanded and contracted species range extensions, and new trophic pathways may each affect biodiversity, the population status of key species, and relations between humans and marine resources. As environmental change continues, can we anticipate how future Arctic ecosystems will compare to those of the past and present? Will the effects of a changing climate be the same across various Arctic regions? Organizers welcome presentations from all regions of the Arctic examining the drivers, rates, processes, and mechanistic controls that impart structure on any aspect of the high-latitude marine ecosystem.
- February 2020. AGU/ALSO Ocean Sciences Meeting Town Hall organization (with AOOS, USARC and DBO) and participation: "Scientific Responses to an Ever Faster Changing Arctic: Making the Most of our Collective Research Efforts". With the U.S. Arctic experiencing such unprecedented, rapid change, the objective of this town hall was to provide an opportunity for the scientific community to informally discuss causality and linkages across results from recent field work and studies, including if a "new normal" for the Arctic can be determined and what this might look like. We would also like to see proposed actions developed for moving forward with coordinated research efforts, ideas for emerging research. And observing needs, and suggestion or how we can best oorganize ourselves to deliver the data and information products that northern communities, resource managers, industry, first responders, and other decision makers will need.
- December 2021. Acoustical Society of America biannual meeting: "Relationship between vessel speed and sounds levels in the Bering Strait." Abstract: Vessel speed limits have been proposed as a means of reducing underwater ship noise, however it is unclear how effective such a measure would be in the Bering Strait, a natural bottleneck for ships transiting into the Arctic from the Pacific Ocean. In this study, we examine how ship noise varies with vessel type and speed using Automatic Identification System (AIS) data collected from vessels traveling through the strait along with acoustic recordings from three moored hydrophones. We matched recordings with

ship noise to individual vessels that passed within 100 km of each hydrophone in June through November 2013–2015. A total of 67 sound files were analyzed, with tug (*n* = 21) and cargo ships (*n* = 16) as the most common vessel type observed in our dataset. Sound levels for each vessel were calculated and compared as a function of vessel type and speed. The results of our study could inform policymakers and managers on the effectiveness of vessel speed limits on reducing ship noise in a sensitive Arctic habitat.

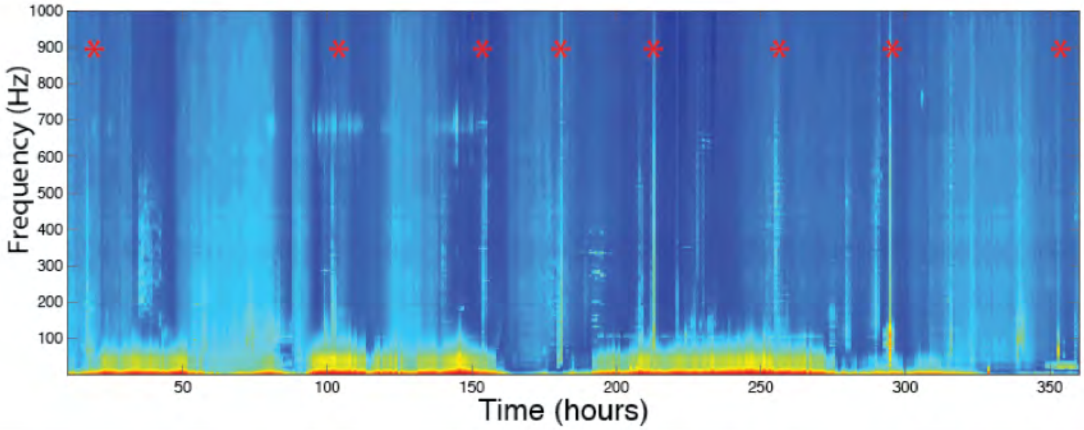
- January 2021. Presentation in "Looking across borders: past, present and future US Russia collaboration in the Bering Sea" during a remote session associated with the Alaska Marine Science Symposium in January 2021.

Synopsis ASGARD project marine mammal studies

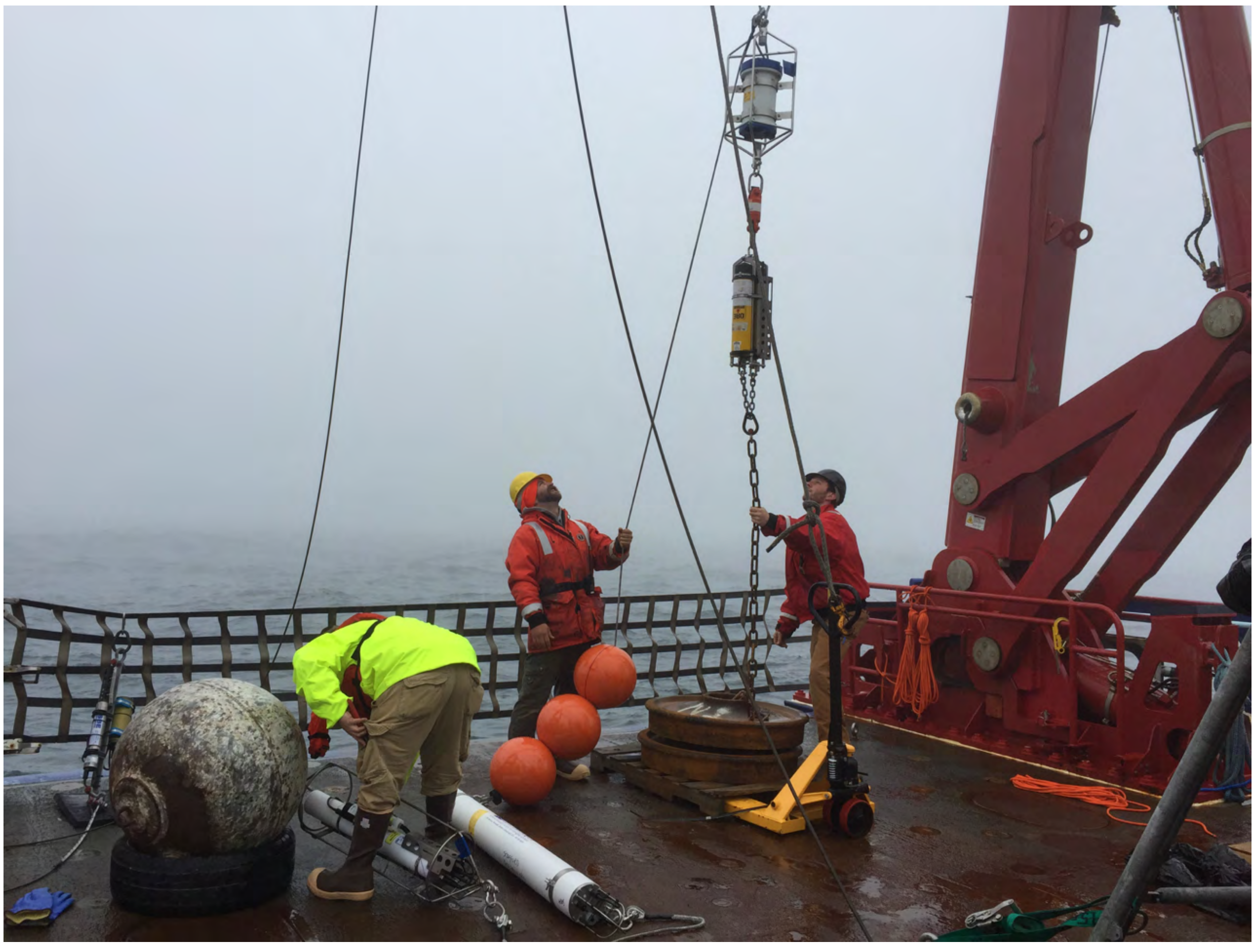
Why we did it
Sea ice is one of the defining characteristics of the Arctic Ocean, and while its timing and extent has already undergone significant human-induced changes, it is projected to further decline in the coming years. The ASGARD project was designed to better refine our knowledge of carbon and nutrient dynamics on the northern Bering and Chukchi sea continental shelves in the face of changing sea ice. The fundamental science question we addressed is: What regulates variations in carbon transfer pathways and how will the changing ice environment alter these pathways and ecosystem structure, including that of upper trophic animals, in the Pacific Arctic and beyond?

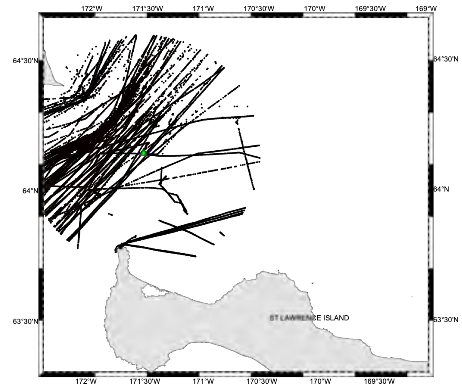
What we did
The ASGARD study consisted of ship-based and mooring-based studies that collected observations of: heat, salt, nutrients and plankton carried by ocean currents; phytoplankton primary productivity; zooplankton growth/reproduction, respiration and fecal pellet production rates; particle deposition rates from the water column to the seafloor; quality of organic matter deposited to the seafloor; benthic respiration and organic matter decomposition rates; abundance and biomass of benthic microbial and metazoan fauna; distribution of fishes at different life history stages; and underwater sound and seasonal distributions of marine mammals. We sailed to the northern Bering and southern Chukchi shelf in 2017 and 2018 on R/V Sikuliaq, occupying "process" stations at which experimental work was carried out, and "survey" stations at which we collected a reduced set of observations. Moorings were deployed in the water from June 2017 to August 2019.

What we learned and why it matters
Ample supplies of nutrients delivered to the Southern Chukchi Sea through Bering Strait fuel a high level of Chukchi shelf primary productivity during months in which water column light levels are sufficient to maintain phytoplankton blooms. Portions of the region likely exist in a near-perpetual state of patchy phytoplankton blooms from the spring ice retreat all the into the fall. Export fluxes to the benthos are large because large-celled diatoms sink rapidly to the shallow seafloor and because mesozooplankton often are unable to constrain the phytoplankton bloom by grazing. The benthic community carbon consumption and oxygen turnover rates are sensitive to the bottom water temperature and are species- specific. Arctic marine mammals occur more frequently to the west of Saint Lawrence Island than to the east and the overall biodiversity of vocal marine mammals is higher to the west. Further subarctic species were heard well into winter months at all locations. Together, these findings suggest that the future Pacific Arctic ecosystem will adjust in species composition and species abundance in a bottom-up response to environmental change. At the same time, range expansions of sub-Arctic predators into the Chukchi Sea will exert new top-down pressure on both the benthic and pelagic communities. Previously unobserved competition between Arctic and sub-Arctic species will also likely play a role in determining the eventual character of the Chukchi Sea ecosystem. Arctic marine mammals are critical to the food security and cultural and spiritual health of coastal Arctic communities and understanding changes in the timing and diversity of upper trophic bellwether species can be used to understand ecosystem-wide environmental changes.



Long-term spectral average from mooring N4 in Anadyr Strait showing ship passages (*)


Mooring being deployed from the back deck of the Sikuliaq in June 2017



2017 June-November shipping

AIS ship tracks to the west of Saint Lawrence Island in 2017

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Appendix A: ASGARD Project Data

Appendix A contains summaries of data types collected by the ASGARD marine project, methodologies, and their locations.

Table A1. ASGARD cruise marine mammal sightings.

Measurement Parameters	Experiment Location /	DOI
Marine mammal sightings during 2017 cruise (location, date, time, species, number of animals)	Bridge observations	10.18739/A26T0GX06
Marine mammal sightings during 2018 cruise(location, date, time, species, number of animals)	Bridge observations	10.18739/A2NV99B09

Table A2. ASGARD mooring-based measurements.

Measurement Parameters	Instrument	Number of Locations
Water Speed and Direction, Temperature, Signal Strength	Teledyne-RDI 307 KHz ADCP	7 mooring sites*
Temperature, Conductivity, Salinity, Pressure, Chlorophyll *a* Fluorescence,	SeaBird SBE-16+	3 mooring sites
Chlorophyll *a* Fluorescence, OBS, CDOM	Wetlabs Eco-Triplett	3 mooring sites*
Temperature, Conductivity, Salinity, Pressure	SeaBird SBE-37	7 mooring sites*
Sinking fluxes of particulate Mass, Carbon, Nitrogen, and Silica fluxes; Food quality of sinking particles	Hydrobios Sediment Trap	3 mooring sites*
NO3, NO2, NH4, SiO3, PO4	GreenEyes Water Sampler	2 mooring sites*
NO3	Satlantic SUNA V2	3 mooring sites*
Acoustic Backscatter at 38, 125, 200, and 455 KHz	ASL Acoustic Zooplankton Fish Profiler	1 mooring site*
Underwater Sound	AURAL	4 mooring sites*

* = one of the denoted sites includes the CEO mooring site near Hanna Shoal. CEO data are separately archived from the ASGARD data on the Axiom Research Workspace.

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14. ABSTRACT

Ample supplies of nutrients delivered to the Southern Chukchi Sea through Bering Strait fuel a high level of Chukchi shelf primary productivity during months in which water column light levels are sufficient to maintain phytoplankton blooms. Portions of the region likely exist in a near-perpetual state of patchy phytoplankton blooms from the spring ice retreat all the way into the fall. Export fluxes to the benthos are large because large-celled diatoms sink rapidly to the shallow seafloor and because mesozooplankton often are unable to constrain the phytoplankton bloom by grazing. Arctic marine mammals occur more frequently to the west of Saint Lawrence Island than to the east and the overall biodiversity of vocal marine mammals is higher to the west. Further subarctic species were heard well into winter months at all locations. Together, these findings suggest that the future Pacific Arctic ecosystem will adjust in species composition and species abundance in a bottom-up response to environmental change. Arctic marine mammals are critical to the food security and cultural and spiritual health of coastal Arctic communities and understanding changes can be used to understand ecosystem-wide environmental changes.

15. SUBJECT TERMS

Bioacoustics, marine mammals, passive acoustic monitoring, animal vocalization, acoustic tracking, habitat use, acoustic analysis

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