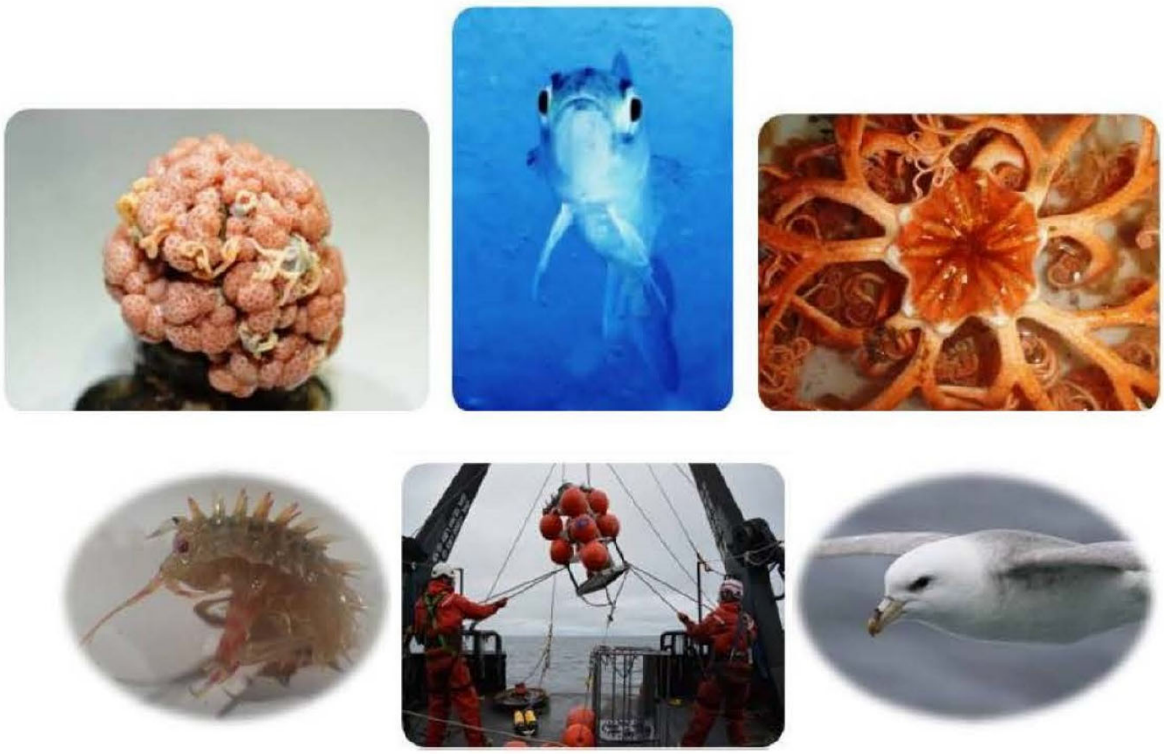
OCS Study
BOEM 2021-017

Initiating an Arctic Marine Biodiversity Observing Network (AMBON)



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Bureau of Ocean Energy Management

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Final Report

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1. Project summary

Living organisms are essential in ocean geochemical and ecosystem processes, but their diversity and complex interactions present challenges to fully grasping those processes. Understanding the role of biodiversity in marine ecosystem processes is a major frontier in ocean science, with implications for global climate models, carbon budgets, sustainable management, public health, and food security. So far, the rapidly growing field of ocean observing has not adequately incorporated coordinated biodiversity measurements. High biodiversity is assumed to foster stable ecosystems because of the high number and complexity of ecosystem functions that a larger number of coexisting species can support. Hence, the development of Marine Biodiversity Observing Networks is a significant step forward in understanding ocean processes and managing, regulating and mitigating human-ocean interactions.

The goal of the Arctic Marine Biodiversity Observing Network (AMBON) project was to build an operational marine biodiversity observation network (MBON) for the US Chukchi Sea continental shelf as a prototype network for the nation. The importance of the Arctic Ocean to global climate and ecosystem processes, and the speed at which climate changes are already occurring in the Arctic, elevate the urgency for coordinated observations of Arctic marine biodiversity. In a system with extremely high seasonal and interannual variability, only long-term datasets can provide the basis to distinguish the "noise" of this natural variability and regular cycles from the directional change driven by climate changes or anthropogenic impacts. The AMBON project employed an end-to-end approach, from microbes to whales, to collect broad spatially distributed biodiversity data in explicit environmental (hydrographic) settings. The AMBON project did not operate in isolation but sampling design and data streams were linked to historical data, where possible, to extend ongoing time series through effective data management. AMBON data and goals were integrated in pan-Arctic monitoring efforts to provide critical

information on the status of Arctic ecosystem health and resilience to decision makers and local, regional and global communities. On a national level, coordination with other MBON programs allowed identification of joint goals towards the development of more cohesive national biodiversity monitoring plans.

Specifically, the AMBON had four primary goals: **1.** To close current gaps in taxonomic and spatial coverage in biodiversity observation on the Chukchi shelf, **2.** To integrate with past and ongoing research programs on the US Arctic shelf into an Arctic biodiversity observation network, **3.** To demonstrate at a regional level how a MBON could be developed in other regions and ecosystems, and **4.** To link with programs on the national and pan-Arctic level. To achieve the new data collection goals, two dedicated AMBON cruises occurred in August 2015 and 2017. In a series of fixed cross- and along-shore transects, we sampled all ecosystem components by combining station-based sampling along the transect grid with survey samples of upper trophic levels (birds, pinnipeds, cetaceans) during transit time. Transects crossed important water masses on the Chukchi shelf to maximize biodiversity collections across environmental gradients (Figure 1). An important purpose of this demonstration project was to evaluate the level of observations necessary to provide data that are representative and have the power of trend detection, to determine biological/diversity metrics that are useful indicators, and to link to other MBONs on the national and global level to achieve a cohesive monitoring project.

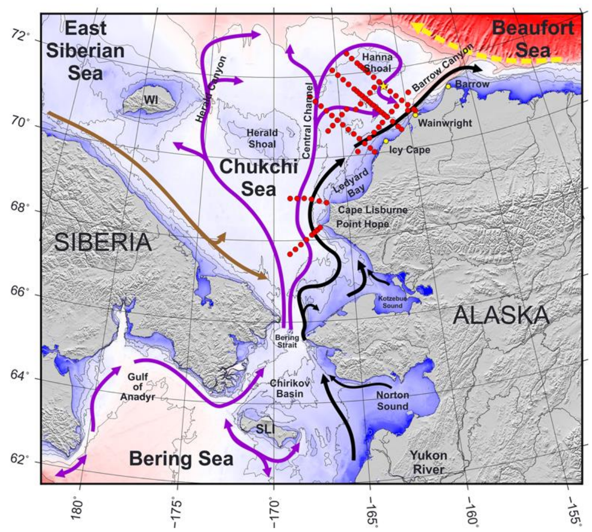

Fig. 1: Map of the Chukchi Sea study region, with red dots indicating the AMBON study sites. Colored arrows show the flow of main water masses: black – Alaska Coastal Current; purple – Bering Shelf-Anadyr Water; brown – Siberian Costal Current.

The AMBON project produced important new data on biodiversity that are currently undersampled (microbes) and on other elements of ecosystem diversity than taxonomic (functional, trophic). Molecular assessments focusing on eukaryotic phototrophic microbes showed that diatom and picoplankton composition is most influenced by temperature. These results indicate that certain taxa are more sensitive to temperature and forecast which taxa may respond to climate warming in the Arctic. The metagenomics shotgun sequencing of microbial samples was a useful tool to document distinct associations of the microbial component with different habitats (e.g., water column, sediment, sea ice), and linking those habitats to specific taxa and even metabolic function.

We also explored other elements of ecosystem diversity than taxonomically-based diversity, namely functional diversity and trophic diversity. These are measures that may actually be closer to the core of the premise of the Biodiversity-Ecosystem-Functioning hypothesis, which states that biodiversity is related to patterns in ecosystem functioning. We advanced a relatively novel approach of linking taxonomic diversity with specific biological traits of taxa that relate to life history, biology and behavior of a species, which in turn relate to specific ecosystem functions. We applied this concept to the benthic community, which occupies a central link in the overarching energy flow of Arctic shelf systems. We found that distinct biological traits characterized the Chukchi Sea epibenthos and they related specifically to resource use and recovery from disturbances. These traits were particularly related to the environmental conditions of grain size, water column characteristics such as temperature and salinity, and depth. A specific element of functional diversity are trophic interactions. We investigated the effects of the diversity of detrital food sources and their use by benthic feeding types on ecosystem structure and energy flow of the Chukchi shelf. The importance of organic matter deriving from terrestrial sources through coastal erosion and river discharge as well as organic matter from bacterial production to the detrital pool on the Chukchi Sea shelf are little understood but seem essential components of benthic invertebrate diets. We found that these additional detrital sources have the ability to stabilize components of the food web dependent on the benthos (i.e., up to megafauna such as gray whales and walrus) against the predicted weakening in pelagic benthic coupling on Arctic shelf systems.

One network aspect of the AMBON project was to maintain close linkages to other past or ongoing projects so that time series of biological observations could be continued or spatial scales of observation could be expanded. Environmental conditions on the shelf over the past 100 years have experienced an extension of the ice-free season from greater uptake of heat in spring months and greater ocean-to-atmosphere heat fluxes in fall over the past 20 years. AMBON data were also instrumental in establishing biodiversity patterns over space and time of a number of different ecosystem elements. A 10-year time series of zooplankton in the northern Chukchi Sea showed overall high interannual variability. However, some fractions of the community decreased and community composition changed over that time period. Changes were related to the presence of warmer water masses, illustrated specifically during the particularly warm 2017 AMBON year. We used AMBON meroplankton collections to complement collections from other years so we could identify the connection between larval dispersal and the distribution of adult benthic populations. These larval dynamics can inform us about the potential of larval recruitment to replenish adult benthic populations after a disturbance, or the potential of sub-arctic or temperate species to invade the Arctic Chukchi shelf. Analyzes showed that adult populations were unlikely to be limited by larval dispersal and the highly advective nature of the shelf system brings in an abundance of sub-arctic taxa. At a higher trophic level, seabird populations that forage on these zooplankton communities decreased in the northern Bering but increased in the southern Chukchi Sea, reflecting a shift in productivity under warming conditions in the past decades. An ecosystem-wide assessment of patterns over time did not only show changes in various ecosystem elements in relation to environmental warming, but also indicated that the system may be reaching a tipping point from which the system may not be able to switch back during cooler conditions.

Combined datasets from multiple years from multiple projects also allowed us to evaluate life history parameters of ecologically important fish and shellfish species. Juvenile Arctic cod select rearing habitats based on temperature and salinity, while adult populations segregate mostly by depth. Arctic cod juveniles hatch over the course of several months in a bet-hatching strategy that increases the potential of juvenile survival under unpredictable and variable conditions in the Arctic. Gathering data from multiple programs on snow crab distribution and size-frequency distribution we re-evaluated the calculations and conclusions of the Arctic Fisheries Management Plan about the viability of a snow crab fishery in the Arctic. We confirmed that current snow crab biomass is insufficient to support fisheries harvest and body size is significantly smaller than legal harvest size of snow crab in effect in the Bering Sea. This is important information for future management of fisheries resources in the Arctic.

One goal of the AMBON project was to initiate the development of a sustainable biodiversity observing network in the Arctic. Work in the Arctic is extremely limited by the time the region is accessible due to sea ice cover or adverse weather and by the high cost associated with sampling in the Arctic. This makes it especially important to run sensitivity analyses on the sampling design for the development of a sustainable program that is powerful enough to detect change. The spatially explicit design of the AMBON station coverage in the Chukchi Sea was ideal to set the stage for a variety of simulation models to optimize the detection of patterns in biodiversity or change in diversity on the Chukchi shelf. We have done this for a variety of ecosystem elements as they differ in their spatial distribution and mobility, which can influence the appropriate sampling design. Most ecosystem elements showed distribution trends associated with the southern versus the more northern Chukchi shelf study region, indicating that both regions should be sampled and that different designs may be optimal for the two regions. Most ecosystem elements showed patterns across the shelf, forming more coastal assemblages and more mid-shelf assemblages, confirming that a cross-shelf transect design is particularly useful for a Chukchi Sea Biodiversity Observing Network. Benthic invertebrates are considered little or moderately mobile; their biodiversity assessments were sensitive to a modeled reduction in spatial sample coverage. A reduced design could still be representative of the biodiversity patters if sampling included the northern and southern study region and if cross-shelf transects were maintained. In contrast, demersal fishes are more mobile and disperse over greater regions. Hence, their distribution patterns were relatively unbiased by a reduction in sample coverage for the representation of the more common species but a reduced sample design was less robust in detecting changes in rare species. This could influence the power of detection of invasive species, a common concern in the Chukchi Sea as it received migrating species from the south. Seabirds are a highly mobile ecosystem component and we assessed if and how a more spatially restricted observation design could adequately represent patterns in seabird community structure. Most of the seabird communities could be detected with more focused observations but some of the long-distance migrants were only adequately sampled with a larger design such as AMBON. We have started to develop a robust modeling approach with which to test multiple sampling design simulations across many ecosystem components. In a different approach, we also evaluated how complementary observing approaches (year-round stationary; hotspot focused; large scale coverage) can provide ecosystem information at a resolution and depth that a single design cannot provide.

AMBON is part of several different international networks that link biodiversity information on a pan-Arctic scale. For example, several AMBON PIs are part of the Arctic Council's Circumpolar Biodiversity Monitoring Program and, among others, contributed AMBON data to a large-scale assessment of biodiversity information report that is used to inform national management plans. Equally, AMBON contributions to the development of Integrated Ecosystem Assessments (IEA) of various Arctic regions are examples of how the biodiversity observations from the AMBON project contribute to ecosystem management. International Arctic science coordination is essential so that the assembly of knowledge from different nations can be optimized. For this, AMBON PIs engaged intensively in the Pacific Arctic Group (PAG) and the Ecosystem Studies of the Subarctic and Arctic Seas (ESSAS).

On a national level, AMBON investigators were engaged with the other national MBON projects in an effort to discuss elements that would contribute to the general design of a national MBON. Given the vastly different structure, dynamic and function of various marine ecosystem types that are being investigated in the national MBONs, a "one size fits all" approach is likely not appropriate. As a group, we identified common metrics that can form a unifying basis for the development of a national MBON concept. Specifically, environmental DNA (including unifying procedures), data management goals, and possible application of satellite metrics to define seascape categories were common metrics among all MBONs. Through both international and national networking, the AMBON project has engaged in a meaningful way with endusers of the biodiversity information created through the project. For AMBON, this connection has been particularly strong with the Bureau of Ocean Energy Management (BOEM), the federal entity managing oil and gas development in the Arctic.

The AMBON program engaged in a variety of outreach activities. One group we interacted with regularly were indigenous subsistence harvest groups living in the Arctic coastal regions bordering the Chukchi Sea. The biodiversity information gathered through the AMBON project is of great relevance for these communities as healthy ecosystems are the foundation of a subsistence lifestyle. AMBON investigators regularly informed community representatives during co-management information sharing venues. Other information sharing occurred through participation in scientific workshops and conferences, during public lectures, and K-12 classroom visits.

Data management had a high priority for the AMBON project and was assisted by the Axiom Data Science group, the technical partner to the Alaska Ocean Observing System. Physical, chemical and biological datasets from the 2015 and 2017 AMBON cruises were processed with metadata records using NOAA-compliant ISO 19115 standards in preparation for data archiving. All biological datasets were transformed (or are pending) into the Darwin Core format for submission to the Ocean Biogeographic Information System (OBIS). AMBON datasets have been curated and are publicly accessible through the MBON Data Portal.

In summary, the AMBON project created important Arctic biodiversity information across multiple ecosystem components from microbes to whales. AMBON collections extended observations of ecosystem elements that are not currently sampled through other programs, e.g., including microbial diversity, functional diversity, and trophic diversity. In addition, our data collections contributed to long-term time series of some ecosystem elements that allowed us to determine patterns of interannual variability and assisted with evaluating tipping points in ecosystem functioning. We also used the spatially extensive AMBON sampling grid to model the biases and power of detection of reduced sampling designs that could be more time- or cost-efficient to support a sustainable Arctic observing design. AMBON is part of several international and national networks, including national MBON programs, to share important biodiversity observations that can assist with harmonizing observing systems across pan-Arctic scales and to inform national management. Open access data sharing and outreach to multiple stakeholder groups, including Alaska indigenous communities, were important venues to share AMBON results.

2. Specific accomplishments

Specific accomplishments of the AMBON project are presented here aligned with the major objectives listed above, although some activities and results bridge more than one objective. For work that has resulted in a peer-reviewed publication, is completed as a student thesis, is currently in peer review, or is in the final stages of preparation for submission, we provide the abstract and attach the full document to this report. Other work in progress is presented here in detail inside the report. AMBON project PI names are in bold in the author list and students funded through the AMBON project are underlined. We ask that work that is currently under review or in preparation to not be publicly distributed at this time.

Objective 1: To close current gaps in taxonomic and spatial coverage in biodiversity observation on the Chukchi shelf

While many ecosystem elements are regularly being assessed during Arctic work, little focus has been paid to biodiversity of these elements. In particular, microbial diversity is little known, as are other aspects of diversity than taxonomic diversity. Therefore, we added novel assessments in microbial, functional, and trophic diversity in the Chukchi Sea in addition to continuing traditional taxonomic observations.

a. Microbial community composition

One of the ecosystem components that is severely understudied in the Arctic, as in many other marine ecosystems, is microbes. Despite the presence of about one million bacteria per milliliter seawater, and the myriad of unique microbial metabolic processes that sustain ecosystem function in the ocean, our understanding of microbe biodiversity is extremely limited. We investigated this microbial community using shotgun metagenomics sequencing. AMBON investigator ***Collins*** wrote an interactive web viewer for amplicon sequencing data called Microscape (available at https://cryomics.shinyapps.io/microscape/). Users can select particular taxa or samples and view their distributions on a "metacommunity map", a multivariate ordination where each sample is a point and the points are arranged into the map using the t-SNE algorithm based on similarity of species compositions. Colors represent different organisms (Figure 2). The database includes samples from several other field campaigns in addition to the 2015 and 2017 AMBON data, such as ASGARD (2017, northern Bering and southern Chukchi seas), Chukchi Borderlands (2016, north of Chukchi shelf), Seward Line (2015-2017, Gulf of Alaska), and others. The DNA was amplified with three separate primers targeting the 16S rRNA gene (bacteria and archaea), 18S rRNA gene (eukaryotes), and the Internal Transcribed Spacer (ITS; all organisms). Sequences were identified by comparison to the SILVA taxonomy database.

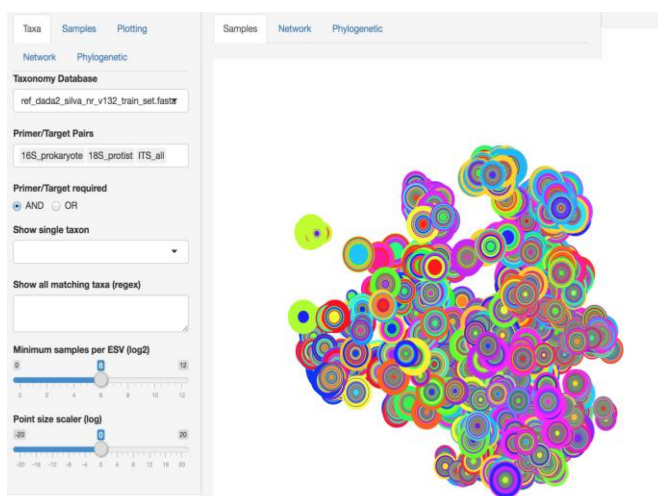

Fig. 2: Microscape of microbes collected during the AMBON cruises, ordinated based on DNA similarity.

We used the microscape approach to delineate the microbial community collected during the AMBON cruises (with the addition of a sea ice community collected elsewhere in the northern Chukchi Sea for contrast). The ordination showed the distinct community composition based on habitat associations, clearly separating free-living (0.2 – 3 µm), particle-attached (> 20 µm), sediment, and sea ice microbes

(Figure 3). This represents the different functions and metabolic pathways these microbes fulfill in those habitats.

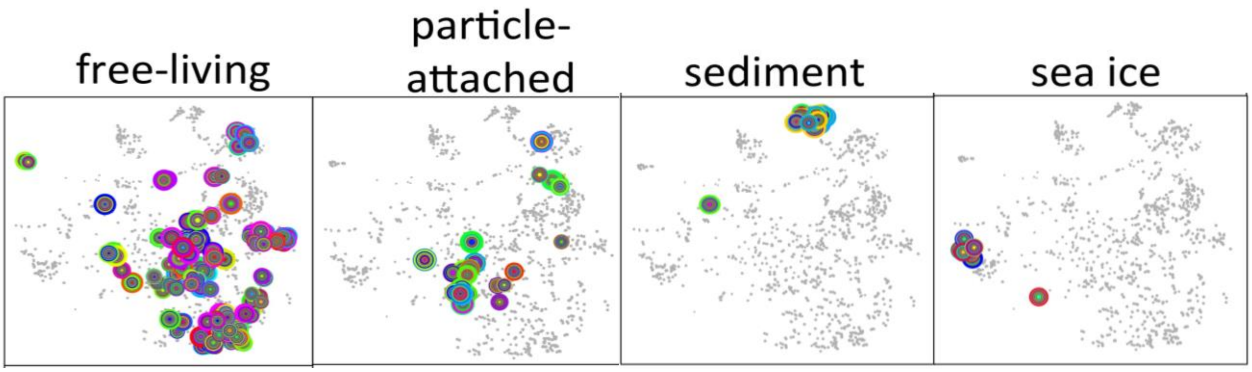

Fig. 3: Microscape of microbial communities from the AMBON collections based on DNA sequencing. Communities are highlighted by their habitat association of free-living, particle associated, sediment associated, or as part of the sea ice community (samples collected in the Chukchi Borderland region in 2016).

Equally, these communities can also be distinguished based on their larger taxonomic groupings and biogeographic affiliation (Figure 4). Within each group, individual species (OUT) are identified in different colors. Size of the bubble is proportional to relative abundance in the sample. The left two panels are algae, the two center panels are heterotrophic bacteria, and the two panels on the right are metazoa. *Chaetoceros* is a genus of diatom that is often dominant in phytoplankton communities in the Chukchi Sea. *Alexandrium* is a dinoflagellate genus that contains harmful algal bloom-forming species and is of specific interest for indigenous communities of the Arctic who subsist heavily on marine resources. SAR11/*Pelagibacter* is a clade that includes the most common bacterium in the world's oceans. SUP05/*Thioglobus* is a clade that includes a common sulfur-cycling bacterium. Metazoa can also be detected based on "eDNA", the presence of DNA in the environment from sloughed cells, etc. *Polychaeta* is a taxonomic group within annelid worms that often are very common in the benthos or represented by pelagic larval stages, and *Maxillopoda* is the taxonomic group within the crustaceans that include copepods, the dominant zooplankton group. These taxon distributions can be matched with habitat associations (assessing Figures 3 and 4 combined); for example, *Chaetoceros* was

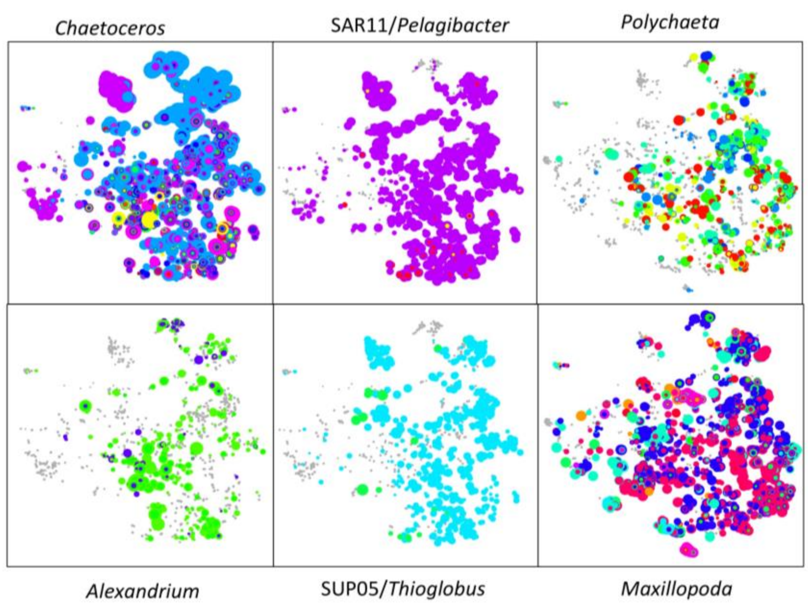

Fig. 4: Microscapes of particular taxonomic groups based on DNA sequencing. Colors within each group indicated different taxa. Presence and abundance of these groups can be matched with habitat associations depicted in Fig. 3.

commonly present in sea ice while *Alexandrium* was not. *Alexandrium* was, however, present in sediments, likely as dormant cysts, the presence of which was hitherto unconfirmed but is of great interest because of the ability of these cysts to emerge under favorable conditions (e.g., warming).

We also linked metagenomics to large-scale biogeographic patterns in metabolic functional potential, using hierarchical clustering of thousands of genes sequenced by shotgun metagenomics (Figure 5). Here, we display the relative abundance of genes associated with nitrogen utilization (top panel), with genes by columns and samples in rows. Two prominent groups of gene expression were evident, associated with sampling stations in the northern and southern Chukchi Sea. This analysis shows that Arctic marine microbial community functional potential changes with seascape. The abundance of individual gene expressions can also be plotted in relation to environmental conditions to determine if certain functions relate more to specific water masses. We used shotgun metagenomic sequencing on seawater samples that were filtered through successive 20 µm, 3 µm, and 0.2 µm filters to capture free-living and particle-attached communities. This example shows the relative abundance of glutamate synthase, an essential gene in the pathway of nitrogen assimilation into proteins in bacteria. It shows that the gene is much more highly represented in the free-living fraction (containing mostly bacterial DNA) compared to the particle-associated fractions (containing mostly algal DNA).

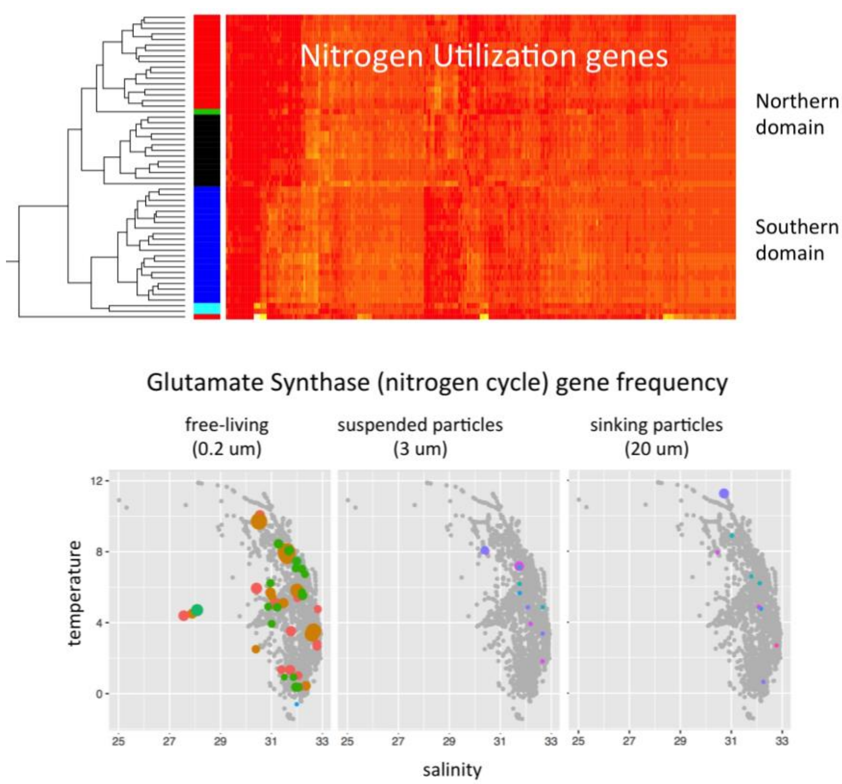

Fig. 5: Metagenomic shotgun sequencing of microbes in the Chukchi Sea to assess the distribution of metabolic function associated with nitrogen uptake across the Chukchi Sea and with water mass characteristics.

b. Phototrophic eukaryote community structure

Part of the microbial component during the AMBON project was investigated as the topic of a Master's student thesis in Oceanography at the University of Alaska Fairbanks. The sample collection from the AMBON project was complemented with additional samples from other projects to expand seasonal and spatial coverage of the dataset. The study showed strong association between environmental variables, especially temperature, and the eukaryotic microbial community composition. The thesis is currently in the process of being prepared for submission to an Arctic special topic issue in *Deep-Sea Research II*.

Full thesis: **Appendix 1** of AMBON Final Report

Diversity and community structure of eukaryotic phototrophs in the Bering and Chukchi Seas
Rachel M. Lekanoff, Thesis in partial fulfillment of requirements for the degree of Master of Science in Oceanography, University of Alaska Fairbanks

This work is currently in preparation for publication in Deep-Sea Research II (by *Lekanoff R.M.,* ***Danielson S.L.,*** *McDonnell A.,* ***Collins, R.E.***)

Abstract
The phytoplankton of the Bering and Chukchi seas support highly productive ecosystems characterized by tight benthic-pelagic coupling. In this study, we focus on the northern Bering and Chukchi seas, considering them as one ecosystem. This community has historically been dominated by diatoms; however, climate change and accompanying warming ocean temperatures may alter primary producer communities. Using metabarcoding, we present the first synoptic, high-throughput molecular phylogenetic investigation of phytoplankton diversity in the Bering and Chukchi seas based on hundreds of samples collected from June to September in 2017. We identify the major and minor taxonomic groups of diatoms and picophytoplankton, relative abundances of genera, exact sequence variants (201 for diatoms and 227 for picophytoplankton), and describe their biogeography. These phylogenetic insights and environmental data are used to characterize preferred temperature ranges, offering insight into which specific phytoplankton (*Chaetoceros*, *Pseudo−nitzschia*, *Micromonas*, *Phaeocystis*) may be most affected as the region warms. Finally, we investigated the likelihood of using shipboard CTD data alone as predictive variables for which members of phytoplankton communities may be present. We found that the suite of environmental data collected from a shipboard CTD is a poor predictor of community composition, explaining only 12.6% of variability within diatom genera and 14.2% variability within picophytoplankton genera. Clustering these communities by similarity of samples did improve predictability (43.6% for diatoms and 32.5% for picophytoplankton). However, our analyses succeeded in identifying temperature as a key driver for certain taxa found commonly throughout the region, offering a key insight into which common phytoplankton community members may be affected first as the Alaskan Arctic continues to warm.

C. Epibenthic functional composition

In addition to traditional taxonomic diversity, other measures of diversity are important and were explored within the AMBON project. One of those measures is functional diversity, where taxa are classified by various functional traits that relate to particular ecosystem functions. With the Chukchi shelf being a benthic-dominated system, we explored these biodiversity-function relationships for the shelf epibenthos. For a larger system perspective, we added epibenthos community data from the Beaufort Sea shelf to contrast these functional relationships between two adjacent shelf systems that experience some similar conditions (high Arctic seasonality) and a similar regional species pool but differ in specific attributes of the shelf system (productivity, shelf width, etc.) and contain some different local species. Epibenthic functional composition was different between the two shelf regions, emphasizing distinctly different functionality of two adjacent systems. While functional and taxonomically based patterns between the two shelf systems were overall similar, taxonomic differences were stronger, emphasizing that regionally different species can fulfil similar ecosystem functions. This work composed the first chapter of a PhD thesis in Marine Biology at the University of Alaska Fairbanks.

Full publication: **Appendix 2** of AMBON Final Report

Comparison of functional diversity of two Alaskan Arctic shelf epibenthic communities

Sutton, L., ***Iken, K., Bluhm, B.A., Mueter, F.J.*** 2020. *Marine Ecology Progress Series* 651: 1-21 (feature article)

Abstract

Alaskan Arctic shelf communities are currently experiencing dramatic changes that will likely affect ecosystem functioning of Arctic marine benthic communities. Here, functional diversity based on biological traits was used to assess differences and similarities in ecosystem functioning be - tween 2 shelf systems that are geographically close but vary in many environmental influences: the Arctic Beaufort and Chukchi Sea epibenthic communities. We hypothesized that (1) patterns of functional composition and diversity metrics reflect patterns in taxonomic composition and diversity metrics in these 2 shelf communities; and (2) patterns in functional diversity metrics are distinct between the 2 shelves. We evaluated 9 biological traits (body form, body size, feeding habit, fragility, larval development, living habit, movement, reproductive strategy, sociability) for 327 taxa in 2014 and 2015. For each trait, multiple modalities (specific expressions within a trait) were considered. Patterns in functional diversity metrics on both shelves reflected those in taxonomic diversity metrics. However, shelf communities were more similar in functional than in taxonomic composition. Beaufort Sea communities had higher functional dissimilarity and functional evenness driven by differences in the modalities within body form, body size, larval development, and reproductive strategy. These traits primarily affect nutrient cycling, energy turnover, and recovery from disturbances, suggesting a stronger potential for future maintenance of ecosystem function, and indicating a more even use of resources in the Beaufort Sea. The combination of functional and taxonomic diversity metrics enabled a comprehensive understanding of how ecological niche space is used and how epibenthic communities function in Alaskan Arctic shelf systems.

d. Environmental filters of epibenthic functional composition

We are expanding the work on functional diversity (Objective 1c) and are currently in the process of analyzing functional diversity patterns in Arctic benthic shelf communities in relation to environmental variables. This analysis lays important groundwork to later be able to predict how ecosystem function based on biodiversity may change in a system where community composition is strongly influenced by continued climate change. We found that epibenthic community function is strongly influenced by the environmental conditions on the Chukchi shelf, which may also present an environmental filter on biological invasions from the south, an increasing concern for Chukchi Sea ecosystem functioning under warming conditions. This work presents the second chapter of a PhD thesis in Marine Biology at the University of Alaska Fairbanks. The work is currently in the advanced stages of preparation for submission to Functional Ecology.

Full manuscript draft: **Appendix 3** of AMBON Final Report

Environmental filtering leads to trait convergence: a functional trait approach in Arctic benthic communities

Sutton L, ***Mueter F, Iken K***. in preparation for submission to Functional Ecology

Abstract

Community assembly theory states that species assemble non-randomly as a result of dispersal limitation, biotic interactions, and environmental filtering. We postulate that this concept also applies to the functional composition based on biological traits of a community. Strong environmental filtering likely leads to local assemblages that are similar in their functional traits (higher trait convergence) while functional traits will be less similar (high trait divergence) under more benign environmental filters. Here, community assembly theory was applied to Arctic Chukchi and Beaufort Sea shelf epibenthic communities that are geographically close but functionally and environmentally dissimilar. The Beaufort Sea generally has more dynamic abiotic influences compared to the Chukchi Sea, which would tend to lead to a stronger environmental filter. We hypothesized that 1) the Beaufort Sea has a stronger environmental filter on functional composition compared to the Chukchi Sea, and 2) stronger environmental filtering will lead to higher trait convergence. Environmental drivers were compared to functional composition based on biological traits and to trait convergence within each shelf. Contrary to our first hypothesis, functional composition in the Chukchi Sea was more highly correlated with environmental gradients compared to the Beaufort Sea, with 36% and 27% of the total functional variance explained, respectively, leading to a stronger environmental filter in the Chukchi Sea. Chukchi Sea epibenthic functional composition, particularly behavioral traits (i.e., feeding habit, living habit, movement) was driven by sediment grain size, temperature, salinity, and depth. In the Beaufort Sea epibenthos, functional composition, particularly feeding habit, movement, and reproductive strategy, was driven by depth and sediment grain size. Higher trait convergence in the Chukchi Sea supported our second hypothesis that higher trait convergence should result from stronger environmental filtering. While environmental filtering in the Chukchi Sea was stronger for the variables measured here, it cannot be excluded that other variables not measured would provide a strong filter within the Beaufort Sea. Strong environmental filtering generally provides a challenging environment and a barrier for invading species, a growing threat for the Chukchi Sea shelf under warming conditions. Weaker environmental filtering, such as on the Beaufort Sea shelf, generally leads to communities that are more structured by biotic interactions, possibly representing niche complementarity from intermediate disturbance levels. These results provide a predictive basis to assess how shelf ecosystem function may respond in response to changing Arctic environmental conditions.

e. Organic matter composition in Chukchi Sea sediments

In addition to expanding routine measurements of taxonomically-based metazoan biodiversity with aspects of microbial diversity (Objective 1a and b) and functional diversity (Objective 1c and d), we also explored how diversified benthic food webs influence ecosystem function on the Chukchi Sea shelf. The Arctic benthos consists to a large portion of feeders of detrital matter; however, the origins and distribution of this detrital matter at the base of the food web within shelf sediments is unknown. This composition can influence ecosystem functions from carbon cycling, long-term carbon sequestration, to biogeographic cycling, which in turn will influence the community composition and biodiversity of the benthic system. The study found that terrestrial organic matter was much more prevalent than previously thought and found about equal proportions of phytoplanktonic, bacterial and terrestrial organic matter distribution across the upper 5 cm of sediments. This work composed the first chapter of a PhD thesis in Marine Biology at the University of Alaska Fairbanks. The work has been submitted to and is currently in review at a special topic issue in *Deep-Sea Research II* on the Arctic.

Full submitted manuscript: **Appendix 4** of AMBON Final Report

Depth distribution of organic carbon sources in Arctic Chukchi Sea sediments

Zinkann, A-C., Wooller M.J., Leigh M.B., ***Danielson, S.L.,*** *Gibson, G.,* ***Iken, K.*** in review at *Deep-Sea Research II.*

Abstract

Climate-induced changes in the composition of organic matter sources in Chukchi Sea sediments could have major implications on carbon cycling, carbon sequestration, and food sources for lower benthic trophic levels. The aim of this study was to identify the proportional contributions of organic carbon from various primary producers (phytoplankton, terrestrial, and bacterial) to depth-stratified sediments (0 - 5 cm) across the Arctic Chukchi Sea shelf using essential amino acid (EAA) specific stable carbon isotope biomarkers. EAA source distributions had little relationship with environmental variables across the Chukchi shelf and only showed noticeably higher terrestrial proportions in surface sediment at some high-deposition regions in the southern study area. Across all sediment depth strata, the majority of EAA in sediments (~76 %) originated from terrestrial sources and may be indicative of accumulation over time due to slow degradation processes of this source within sediments. The different EAA sources showed no significant differences in proportional contributions with sediment depth except for phytoplankton-derived EAA, which decreased with increasing sediment depth. These patterns indicate a well-mixed upper sediment horizon, possibly from bioturbation activities by the abundant benthos. One EAA source assumed to respond quickly to changing environmental conditions are bacteria. To evaluate if and how bacterial production would respond to elevated temperatures, bacterial production was measured experimentally using phospholipid fatty acid (PLFA) analysis. Bacterial production was initially (first 24 h) higher at 5°C than at 0°C; however, a drawdown of substrate or potential increase in predation activity and viral lysis resulted in bacterial production to subsequently be similar at both temperature settings. Results suggest that terrestrial and bacterial carbon sources may become more prominent in a future, warmer Arctic. Identifying baselines and potential shifts in carbon sources with changes in temperature can aid in the understanding of the consequences of climate change in terms organic matter presence and flow through benthic consumers that use these shelf sediments as feeding grounds.

f. Use of diverse organic matter sources by benthic feeding types

We used our results on organic matter distribution in Chukchi Sea shelf sediments (Objective 1e) to assess the effects of organic matter provenance on benthic feeding types. With the ongoing environmental changes in the Arctic, the influences of different primary production sources that contribute to the detrital pool are expected to change, thus affecting the benthic taxa that will be successful with a changed organic matter supply. Our analysis investigated if feeding type is a useful concept to assess which taxa may be successful under a changing regime of organic matter distribution. The study found that organic matter source use was not consistent within a feeding type, cautioning us against a simplified feeding type approach to understand the diversity of prominent detrital pathways in the Arctic. This work is the second chapter of a PhD thesis in Marine Biology at the University of Alaska Fairbanks. The work has been submitted to and is currently in review at the journal *Food Webs*.

Full submitted manuscript: **Appendix 5** of AMBON Final Report

Does feeding type matter? Contribution of organic matter sources to benthic invertebrates on the Arctic Chukchi Sea shelf

Zinkann, A-C., Wooller, M.J., O'Brien, D., ***Iken, K.*** In review at *Food Webs*

Abstract

Benthic communities play an important role in the nutrient cycling of settling organic matter and provide an energy link to higher trophic levels. These benthic communities are highly dependent on the food sources provided through sinking organic material, with pelagic-benthic coupling particularly strong on Arctic shelf systems. Arctic shelves, however, are experiencing shifts in the timing of sea ice breakup that can have severe implications on the amount and composition of organic matter from different primary production sources supplied to the benthos. The role of benthic invertebrates in processing organic matter is typically classified by feeding types. The goal of this study was to evaluate if benthic invertebrate feeding types are a useful concept for understanding how organic matter from various biosynthetic sources is used by benthic invertebrates across the Arctic Chukchi Sea. We employed essential amino acid (EAA) specific stable isotope fingerprinting to identify proportional contributions of three EAA sources (from bacterial, phytoplankton,

and terrestrial production) as a proxy of carbon sources to the diets of benthic consumers. When grouped by feeding types, the proportional contributions of the three EAA sources were similar among suspension and deposit feeders and predators/scavengers. Different genera within the same feeding type, however, showed significant differences among the EAA sources, indicating that EAA use is genus-specific rather than feeding type-specific. We discuss characteristics other than feeding mode among genera that could account for different EAA use, including mobility, selectivity of available EAA in sediments, and other trophic aspects such as assimilation efficiency. These characteristics provide useful additional considerations when grouping organisms by feeding types. High proportions of terrestrial EAA were found in the majority of benthic genera across all feeding types and characteristics in this study, reflecting the high proportions of this matter source in sediments and confirming that this source is being used by benthic consumers in the Arctic. EAA contributions to various benthic genera across the Chukchi Sea shelf had only weak correlations with environmental variables. While the distinctly different uses of different EAA sources by benthic-feeding genera but not by feeding types may represent high trophic plasticity in Arctic benthic invertebrates, expected climate change-driven shifts in the supply of EAA sources to the Chukchi Sea shelf benthos may still have implications for the composition of benthic communities and energy flow through the benthic food web, including energy pathways that support current top predators.

g. An improved ecosystem model of the Chukchi Sea

We used the information obtained from AMBON ecosystem component collections and the information of the use of different organic matter sources by benthic fauna (Objective 1e and f) to improve an ECOPATH ecosystem model based on energy flow in the Chukchi Sea. This ecosystem model is based on energy flow through the different ecosystem compartments and is a useful tool to understand the immense complexities of the ecosystem from basal production to top predators. It also helps identify areas of insufficient information (what are the assumptions that need to be made to balance the energy flow through a system and are those assumptions realistic?) and allow a mechanism to force the system processes through environmental driver manipulations. This can give valuable information how energy flow may change within a system of altered biodiversity with the impacts of climate changes. We found that a more diversified detrital component in the Chukchi Sea food web would account for some of the imbalances in previous models. Different ecosystem response scenarios of climate warming supported specific hypotheses how biomass allocation within the system would shift across all trophic levels.

Full submitted manuscript: **Appendix 6** of AMBON Final Report

The Arctic Chukchi Sea food web: simulating ecosystem impacts of future changes in organic matter flow
Zinkann, A-C., Gibson, G., ***Danielson, S., Iken, K.*** In review at *Ecological Modeling*.

Abstract

The Chukchi Sea continental shelf is a highly productive inflow shelf of the Arctic Ocean that is experiencing climate warming events and declines in seasonal sea ice cover at one of the fastest rates compared to other Arctic shelves. Climate-induced changes in phytoplankton and ice-algal primary production, inflow of terrestrial matter through riverine discharge and coastal erosion, and increases in bacterial production have previously been predicted to cause shifts in the composition and distribution of organic matter supply and energy flow in this system. The goal of this study was to examine potential shifts in the Chukchi Sea ecosystem energy flow under various future climate scenarios. To address these goals, an existing mass balance Chukchi Sea ecosystem model by was updated by incorporating terrestrial matter as an energy source, especially for benthic consumers. Incorporation of the terrestrial matter component allowed us to adjust current model phytoplankton biomass to better match recent empirical measurements and to update the system-wide mass-balance. We also modeled potential impacts of future climate-driven alterations in the composition and flow of organic matter supply on major ecosystem groups for the 2015 – 2050 period. Iterations showed that climate-driven increased retention of phytoplankton biomass in the pelagic realm would depress

biomass of most benthic-feeding organisms across several larger ecosystem groups (invertebrates, fishes, mammals). However, simulated increases in both terrestrial matter inflow and bacterial biomass have the potential to compensate for some of the reductions in the energy supply from phytoplankton to the benthic food web, as well as to diversify the supply of organic matter to the seafloor. This diversification could make the Chukchi Sea ecosystem more stable to future climate-driven changes.

h. Benthic species identification guides

One of the limiting resources for determining biodiversity in Arctic regions is the uncertainty of species identifications, particularly in high biodiversity ecosystem components such as the benthos. This becomes an issue when trying to recognize invasive species or when combining datasets from different project with different investigators. We used the AMBON project to undertake a concerted effort to document benthic biodiversity in a field-friendly fashion, i.e., in a picture identification catalog. We had started this effort several years ago for the use of our own investigator group but the AMBON project was an opportunity to enhance and share this catalog for the wider Arctic benthic researcher community to use. There are now five chapters of benthic invertebrate identification guides available on the AMBON website https://ambon-us.org/monitoring-projects/): Annelida and other worms, Crustacea, Mollusca, Echinodermata, Miscellaneous Taxa. Identifications of these taxa were based on a multitude of taxonomic experts but a disclaimer at the beginning of each chapter cautions the user that the images provided may not always show the identifying features clearly (some can be microscopically small) and that there are more species present on the Pacific Arctic shelf systems than presented in these guides. We have been testing the value of these guides with the help of our colleagues from the NOAA NMFS/AFSC RACE Division where Arctic benthic invertebrate expertise is limited. We have received the feedback that the guides are invaluable for field identifications, and already we see much more cohesive identifications being produced by research-based efforts and those produced from fisheries trawl surveys.

Full benthic identification guides: **Appendix 7-11** of AMBON Final Report

Appendix 7: Annelida and other worms
Appendix 8: Crustacea
Appendix 9: Mollusca
Appendix 10: Echinodermata
Appendix 11: Miscellaneous taxa

The following plate shows select pages of the five identification guides (Figure 6), the full guides are attached and are also publicly available on the AMBON website (https://ambon-us.org/monitoring-projects/).

Fig. 6: Select pages of the five benthic invertebrate picture guides that are publicly available in full on the AMBON website (https://ambon-us.org/monitoring-projects/)

i. AMBON cross-community analysis

One of the more powerful aspects of the AMBON project is the concurrent collection of biodiversity information across a multitude of ecosystem components. We have begun capitalizing on this unique collection of information on the same spatial and temporal scales but across ecosystem components. A manuscript is in preparation for submission to a *Special Issue in Oceanography* on MBONs: Diversity and species composition across multiple assemblages in the Chukchi Sea. ***Mueter, F.J., Iken, K., Grebmeier, J., Hopcroft, R., Kuletz, K., Collins, E., Cooper, L., Danielson, S.***, (In Prep). We here provide an extended abstract of this work:

Biological communities on the Chukchi Sea shelf are strongly influenced by seasonally varying ice cover and by the advection of Pacific-origin water through Bering Strait. Sea ice covers the Chukchi Sea shelf each winter, but gives way to mostly open water in the summer as winds, seasonal warming and the advection of warmer waters through Bering Strait contribute to largely ice-free conditions by late summer, especially in recent years. Species have adapted to these seasonal extremes, including permanent residents adapted to cold winter conditions, short-lived species that complete their life cycle during the short production season, some long-lived species adapted to poor food conditions for much of the year, and seasonal migrants that capitalize on the high summer production but overwinter south of the Arctic.

Ocean warming, changes in regional winds and increased advection through Bering Strait have accelerated the loss of sea ice in the northern Bering Sea and Chukchi Sea and may be contributing to a potential transformation of the Pacific Arctic (Huntington et al., 2020). This transformation impacts downstream communities in the northeast Chukchi Sea, but the impacts will likely differ among species, communities and ecosystem components, resulting in changing relationships among them. While several biological studies have been conducted in the Chukchi Sea over recent decades, few have provided an integrate assessment across multiple trophic levels on a broad geographical scale. Sigler et al. (2011) characterized zooplankton, pelagic fishes, benthic fishes and invertebrates, and seabirds across the Bering, Chukchi and Beaufort seas using data from a range of years with inconsistent spatial coverage. Another study synthesized results from a localized study across three proposed oil and gas prospects that spanned the transition from a pelagic-dominated system in Pacific origin waters to a benthic-dominated system in Arctic waters (Day et al. 2013). A follow-up study by Sigler et al. (2017) described the zoogeography of the same four assemblages as in the earlier Sigler et al. (2011) work over the northern Bering Sea and Chukchi Sea using data collected during concurrent surveys in 2012, establishing broad nearshore-offshore and north-south gradients in community structure.

Using data from the AMBON surveys, we are building on these efforts to better understand patterns in diversity and community composition within and across a range of assemblages from microbes to seabirds in the central and northeast Chukchi Sea, spanning the transition from Pacific to Arctic origin waters. Our primary objectives were to (1) evaluate spatial patterns in the diversity and species composition of multiple assemblages in the Chukchi Sea, (2) quantify the strength of cross-assemblage connections, and (3) assess linkages between environmental drivers and these assemblages. Ultimately, we aim to better understand how these communities respond to changing environmental conditions, including climate change.

Data were collected during the two AMBON cruises in 2015 and 2017 as described in Iken et al. (2019) and other sections in this report. Here we present selected results from analyses of the 2015 data only. The analyses are currently being updated to include data for all assemblages surveyed in 2017, which includes an additional transect in the previously under-sampled region between Cape Lisburne and Point Lay to provide more complete spatial coverage across the latitudinal gradient across the central and northeast Chukchi Sea shelf.

The assemblages considered for these analyses included the microbial community, zooplankton, benthic macrofauna, demersal fishes and epibenthic invertebrates, and seabirds. All assemblages except seabirds were sampled at discrete stations along cross-shelf and along-shelf transects (Figure 1, 7). For these analyses, seabird data were discretized by aggregating observations at the station level after assigning each transect segment to the closest station. Only surface water samples were used for the microbial community to summarize diversity separately for bacterial and protist assemblages. Microbial data were collected for a subset of the stations sampled by other surveys and were not included in multivariate analyses of community composition. The microbial community was as assessed through eDNA analyses, zooplankton were collected with a 150 µm plankton net, benthic macrofauna were sampled with a van Veen grab, demersal fishes and epibenthic invertebrates were sampled using a bottom trawl, and seabirds were assessed visually along the cruise ship track during daylight hours.

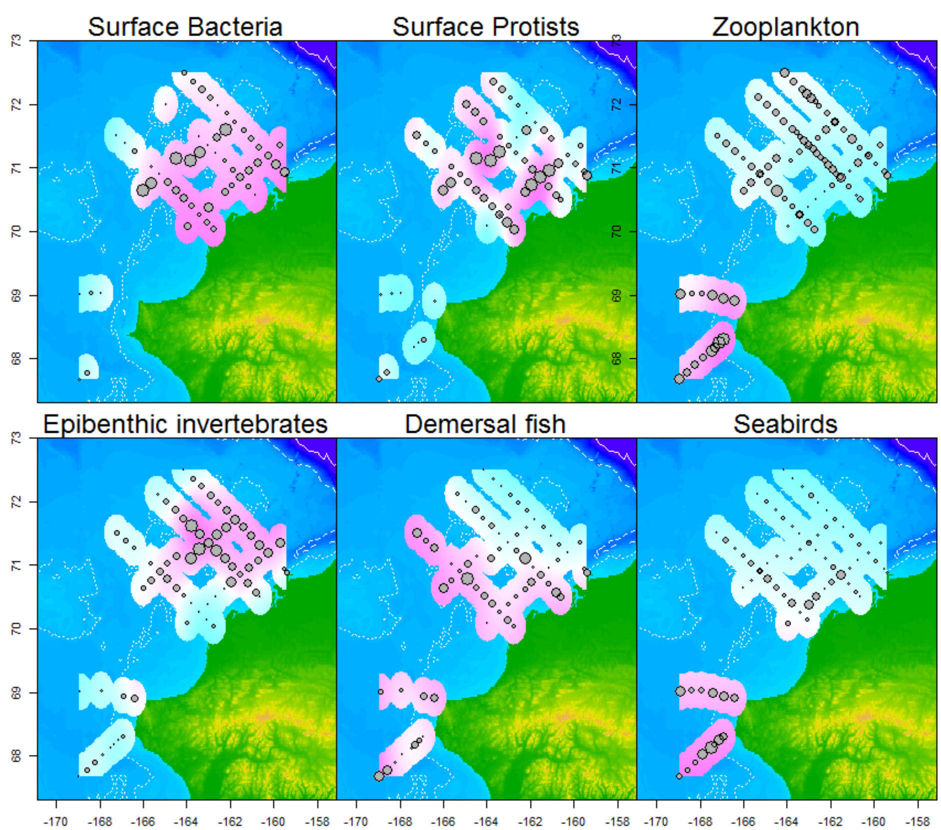

Fig. 7: Spatial gradients in local species diversity of six assemblages sampled during AMBON 2015. Larger circles indicate a higher number of species per sample. Shading reflects smoothed patterns of diversity estimated from a spatial additive model.

Local species richness for each assemblage was simply quantified for each station as the number of species per sample. Species richness was not standardized to sampling effort as the consistent AMBON sampling across ecosystem components resulted in relatively little variability in effort across components and we did not find significant relationships between the number of species and measures of effort (volume filtered, area swept or distance). Spatial patterns in diversity differed markedly among assemblages (Figure 7) with a patchy distribution of richness and generally higher richness in the north for bacteria and protists. An opposite trend of higher species richness in the south was found for both zooplankton and seabird assemblages. Opposite patterns were found in the diversity of demersal fishes and epibenthic invertebrates, with fish diversity being generally higher at stations influenced by Pacific origin waters, while diversity of epibenthic invertebrates tended to be higher in Arctic origin waters (north).

Species composition for each assemblage (excluding microbes) was visualized using a non-metric multidimensional ordination based on the Jaccard index of similarity for incidence data (Figure 8). All assemblages displayed strong latitudinal gradients, but were associated with different environmental variables. Relationships between environmental variables and community composition was quantified and tested for significance using Mantel correlations. Relationships were visualized as vectors in the ordination that reflect the correlation between each environmental variable and gradients in species composition as measured by the ordination axes. Environmental variables included in these analyses were surface and bottom temperatures and salinities, depth and sediment characteristics. Due to strong correlations among sediment variables, sediment characteristics were quantified using a Principal Components Analysis (PCA) of the proportions of the sediment for phi sizes 1-5, total organic carbon (TOC), total organic nitrogen (TON), the C/N ratio, sediment chlorophyll and stable isotope ratios for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). The first two principal components were readily interpretable; PC1 reflected a gradient from fine silt and clay with high TOC, TON and $\delta^{15}N$ to coarser, more sandy substrates with lower organic content, while PC2 reflected a gradient from finer sand to high gravel content with a high C/N ratio.

Benthic communities incl. demersal fish primarily associated with sediment gradients and bottom water type (Figure 8). Surprisingly, zooplankton and seabird assemblages were primarily associated with bottom waters rather than surface waters despite their pelagic habitat. Sediment characteristics were generally correlated with depth and bottom water characteristics and reflected both a nearshore-offshore gradient and north-south gradient.

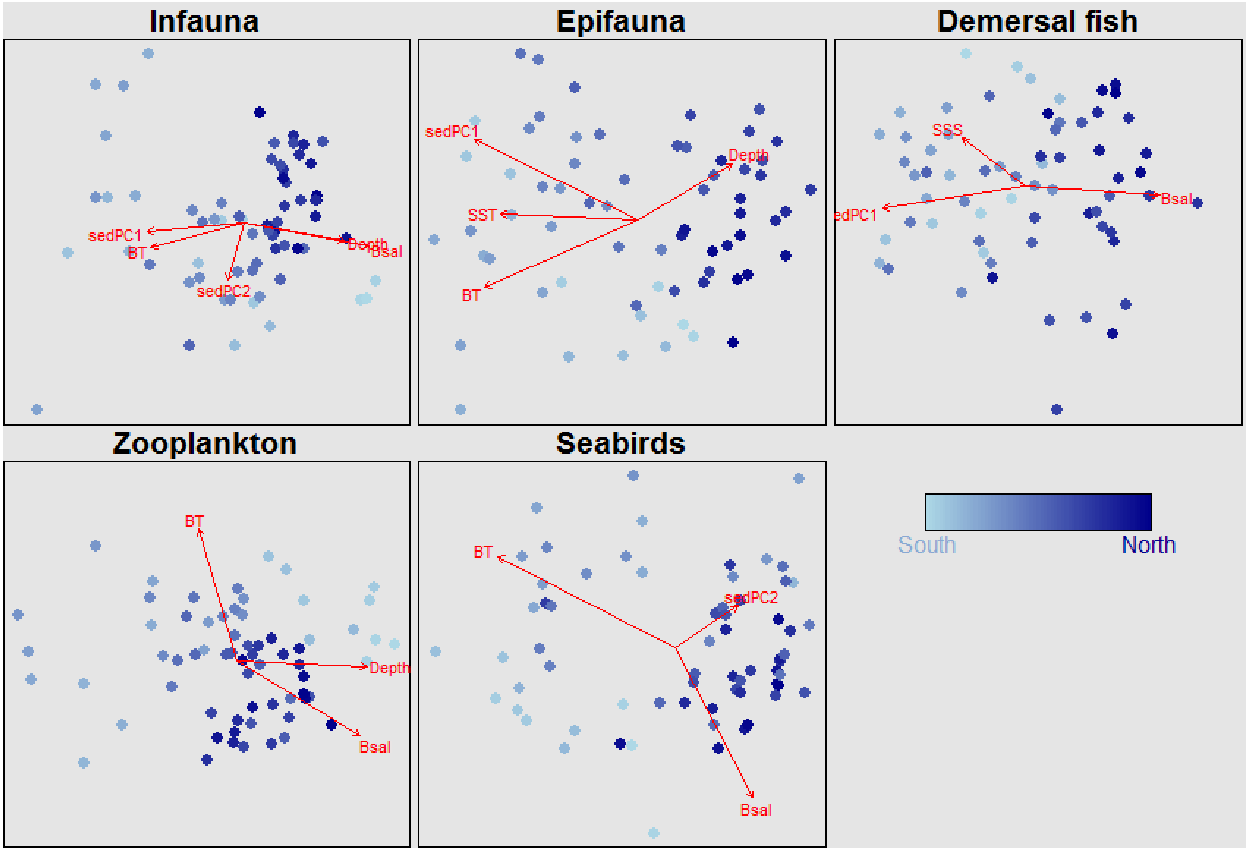

Fig. 8: Ordination of five assemblages surveyed in 2015 in the Chukchi Sea based on multidimensional scaling. Shading denotes latitude to highlight north-south gradients in species composition. Arrows indicate significant relationships between community composition and environmental variables based on correlations between each environmental variable and the ordination axes. Environmental variables included in the analyses were bottom temperature and salinity (BT, Bsal; for benthic communities only), sea-surface temperature and salinity (SST, SSS; for midwater and surface communities only), depth, and simplified measures of sediment characteristics from a Principal Components Analysis (sedPC1, sedPC2; see text).

Linkages across assemblages were quantified using Mantel correlations and showed moderate to strong correlations among the ecosystem assemblages (Table 1), consistent with Sigler et al. (2017). The strongest correlation was observed between benthic infauna (macrofauna) and epifauna (ρ=0.50). The observed association between zooplankton and bottom water characteristics was supported by a strong correlation between zooplankton and infaunal species composition (ρ=0.48). There was also a strong correlation between seabird species composition and zooplankton species composition, but not between the demersal fish community and either zooplankton or fish (Table 1). Key indicator species characterizing each community association were identified using statistical models linking each species in a given assemblage to the ordination axes of another assemblage. We used a generalized additive modeling approach with a Tweedie distribution to account for excessive zero observations in the data to assess the strength of the relationships and ranked species based on the resulting (Pseudo-)R^2 values. Species with an R^2 value of at least 0.2 that were significantly related (95% significance level) to the community ordination were considered potential indicator species. As an example, we show the strong and unexpected associations between three epifaunal species and the zooplankton community (Figure 9).

Table 1: Cross-assemblage Mantel correlations

	Infauna	Epifauna	Fish	Zooplankton	Seabirds
Infauna		<0.001	0.001	<0.001	<0.001
Epifauna	0.504		<0.001	<0.001	<0.001
Fish	0.157	0.414		<0.001	0.032
Zooplankton	0.448	0.352	0.185		<0.001
Seabirds	0.373	0.331	0.080	0.414	

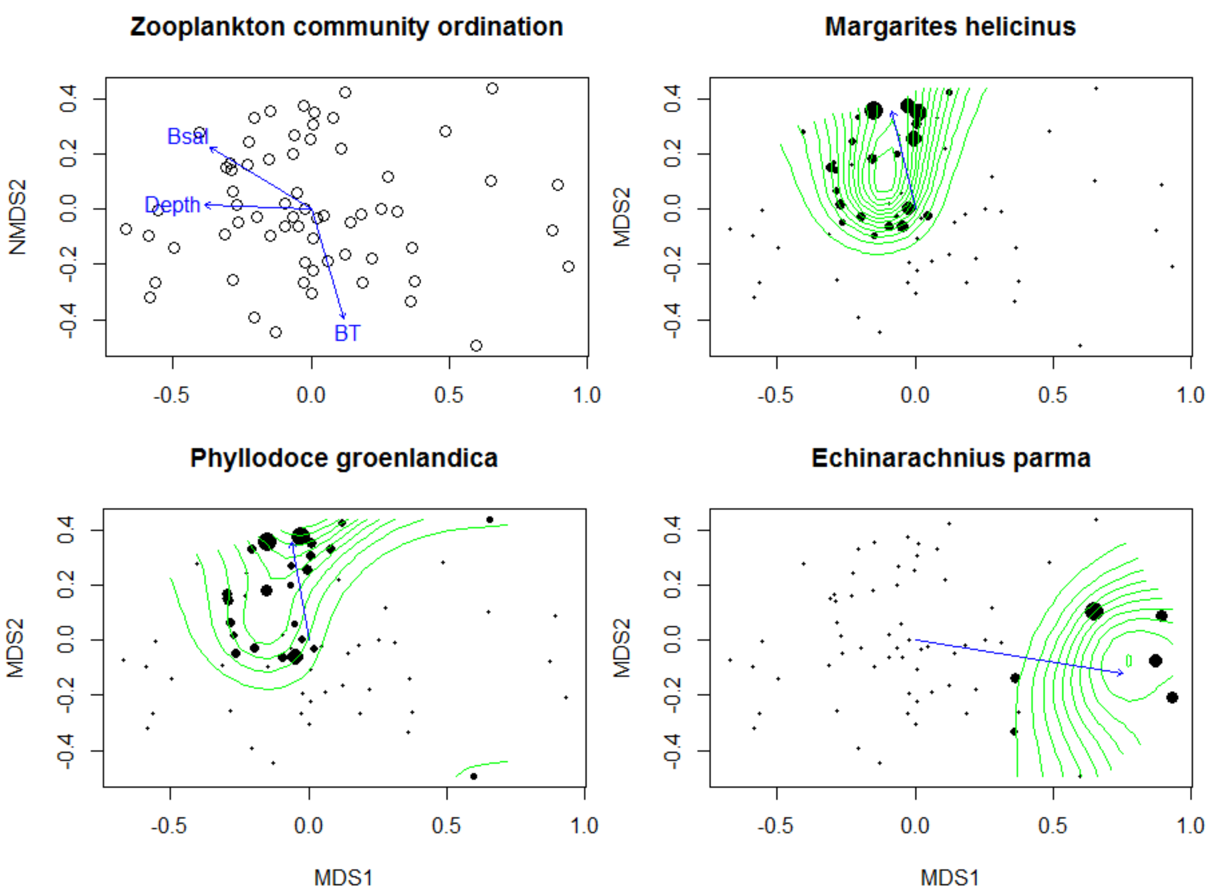

Fig. 9: Non-metric multi-dimensional scaling (NMDS) ordination of zooplankton community (upper left with environmental associations (BT = bottom temperature, BSal = bottom salinity) and associations with three selected epibenthic indicator species that are associated with the zooplankton community. Abundances (square-root transformed catch-per-unit-area) of individual epifaunal organisms that were strongly correlated with the zooplankton community are indicated by the size of the circles. Green contour lines represent fitted values of catch-per-unit-area from Generalized Additive Models that were the basis for evaluating associations (based on R^2 values from the model). Blue arrows represent the linear association of the epifaunal species with the zooplankton community.

References:

Day et al. 2013, *Continental Shelf Research*, *67*:147-165.
Huntington et al. 2020, *Nature Climate Change*, *10*(4): 342-348.
Sigler et al. 2011, *Oceanography*, *24*(3): 250-265.
Sigler et al. 2017, *Deep Sea Research Part II, 135*, pp.168-189.

Objective 2: To integrate with past and ongoing research programs on the US Arctic shelf into an Arctic biodiversity observation network

AMBON investigations did not occur in isolation but we built the collection of many data streams in part on earlier studies to continue valuable time series. This was an important element of the "network" function of the AMBON project and featured strongly into the spatial design of the project. Such time series are essential to be able to assess interannual variability as the background to be able to detect any long-term changes that may be occurring from climate-driven environmental changes. The collaboration with other (past and ongoing) projects also provided significant leverage for the AMBON work, through shared logistics and science planning, which is a key limiting factor for field work in the Arctic.

a. Long-term environmental conditions in the Chukchi Sea

We used AMBON data to contribute to a long-term time series of environmental conditions in the Chukchi Sea. This paper provides environmental context for the AMBON study region by synthesizing the period of record of physical hydrography from the Bering and Chukchi Seas. For the Chukchi Shelf, we documented a significant summer and fall warming over 1922-2018; over the 1990–2018 period the warming rate tripled. The changes in heat are associated with an extended ice-free season, greater uptake of heat in spring months, and greater ocean-to-atmosphere heat fluxes in fall.

Published manuscript: **Appendix 12** of AMBON Final Report

Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves

Danielson, S.L., *Ahkinga, O., Ashjian, C., Basyuk, E.,* ***Cooper, L.W.,*** *Eisner, L., Farley, E.,* ***Iken, K.B., Grebmeier, J.M.,*** *Juranek, L. and Khen, G.* 2020. *Deep Sea Research Part II: Topical Studies in Oceanography*, p.104781.

Abstract

A temperature and salinity hydrographic profile climatology is assembled, evaluated for data quality, and analyzed to assess changes of the Bering and Chukchi Sea continental shelves over seasonal to century-long time scales. The climatology informs description of the spatial distribution and temporal evolution of water masses over the two shelves, and quantification of changes in the magnitude and throughput of heat and fresh water. For the Chukchi Shelf, linear trend analysis of the integrated shelf heat content over its 1922–2018 period of record finds a significant summer and fall warming of 1.4 °C (0.14 ± 0.07 °C decade^{-1}); over 1990–2018 the warming rate tripled to 0.43 ± 0.35 °C decade^{-1}. In contrast, the Bering Shelf's predominantly decadal-scale variability precludes detection of a water column warming trend over its 1966–2018 period of record, but sea surface temperature data show a significant warming of 0.22 ± 0.10 °C decade^{-1} over the same time frame. Heat fluxes over 1979–2018 computed by the European Centre for Medium-Range Weather Forecast (ECMWF) ERA5 reanalysis exhibit no record-length trend in the shelf-wide Bering surface heat fluxes, but the Chukchi Shelf cooling season (October–March) has a trend toward greater surface heat losses and its warming season (April–September) has a trend toward greater heat gains. The 2014–2018 half-decade exhibited unprecedented low winter and spring sea-ice cover in the Northern Bering and Chukchi seas, changes that coincided with reduced springtime surface albedo, increased spring absorption of solar radiation, and anomalously elevated water column heat content in summer and fall. Consequently, the warm ocean required additional time to cool to the freezing point in fall. Fall and winter ocean-to-atmosphere heat fluxes were anomalously large and associated with enhanced southerly winds and elevated surface air temperatures, which in turn promoted still lower sea-ice production, extent, and concentration anomalies. Likely reductions in sea-ice melt were associated with positive salinity anomalies on the Southeast Bering Shelf and along the continental slope over 2014–2018.

Negative salinity anomalies during 2014–2018 on the central and northern Bering Shelf may be related to a combination of 1) long-term declines in salinity, 2) an increase of ice melt, and 3) a decline of brine production. We hypothesize that freshening on the Bering Shelf and in Bering Strait since 2000 are linked to net glacial ablation in the Gulf of Alaska watershed. We show that the heat engines of both the Bering and Chukchi shelves accelerated over 2014–2018, with increased surface heat flux exchanges and increased oceanic heat advection. During this time, the Chukchi Shelf delivered an additional 5–9 x 1019 J yr^{-1} (50–90 EJ yr^{-1}) into the Arctic basin and/or sea-ice melt, relative to the climatology. A similar amount of excess heat (60 EJ yr^{-1}) was delivered to the atmosphere, showing that the Chukchi Sea makes an out-sized contribution to Arctic amplification. A conceptual model that summarizes the controlling feedback loop for these Pacific Arctic changes relates heat content, sea ice, freshwater distributions, surface heat fluxes, and advective fluxes.

b. Decadal patterns of zooplankton communities in the Chukchi Sea

One of the long-term time series the AMBON project continued is the composition of zooplankton in the Chukchi Sea. We assembled zooplankton observations in the northern Chukchi Sea over a 10-year time period, from 2008-2017, including the two AMBON field years. This work is currently in preparation for publication as: Decadal variability in mesozooplankton communities of the Northeastern Chukchi Sea: 2008 – 2017, *Questel JM, Smoot CA, Clarke C,* ***Hopcroft RR***. We here provide an extended abstract of this work:

A decade of continuous fixed-station sampling afforded us to investigate the high level of ecosystem variability on small spatial scales and the architectural role water masses play in shaping these high-latitude pelagic ecosystems. Here, we show how seasonal variability in the timing and prevalence of these water masses shape the composition, abundance, and spatial distribution of zooplankton species spanning a decade of sampling the northeastern Chukchi Sea ecosystem. Data for this work were collected in the northeastern Chukchi Sea during four research programs spanning the open water season from late-July to mid-October: the Chukchi Sea Environmental Studies Program (CSESP) sampled from 2008 – 2014 and conducted 2 to 3 cruises per year, the Alaska Monitoring and Assessment Program (AKMAP) from 2010 – 2011, the Aquila program during 2016 (AQ16), and the Arctic Marine Biodiversity Observation Network (AMBON) during 2015 and 2017. Small-bodied zooplankton were collected with a by paired 150-µm-mesh ring nets of 60-cm diameter hauled vertically from within 3 m of the bottom to the surface. To target larger-bodied and more mobile zooplankton, a set of 60-cm-diameter 505-µm Bongo nets were deployed in a double oblique tow.

Seasonally, the Chukchi Sea shelf ecosystem undergoes a transformation in water-mass characteristics where Winter Water (WW), Modified Winter Water (MWW), and Ice Melt Water (IMW) are replaced by warmer water masses advected into the system (e.g., Warm Coastal Water [WCW] and Warm Shelf Water [WSW]) (Figure 10). The winter water masses MWW, WW, and CSW occupied the lower 5 m of the water column during all years except 2017 when the system was already void of these colder winter features; the AMBON year 2017 was dominated by warmer water masses that extended to the sea floor.

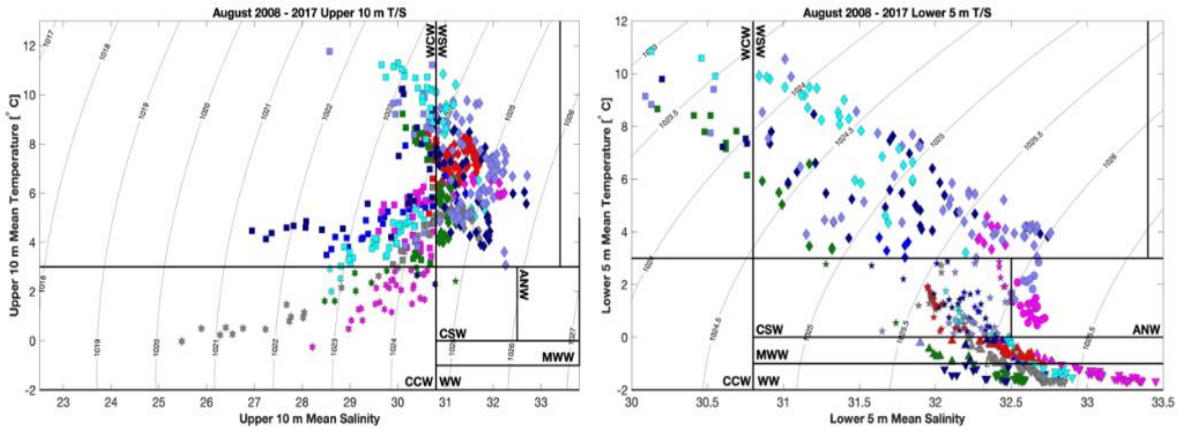

Fig. 10: T/S distributions across the study region for cruises in August 2008-2017. Colors relate to sampling years. Temperature (C) and salinity were averaged over the top 10 m (left panels) and bottom 5 m (right panels) of the water column. Contours depict lines of constant density. Water mass abbreviations are as described in in the text.

In total, 155 unique taxa were recorded for the zooplankton community across the decade of sampling during the open-water season in the northeastern Chukchi Sea. Total zooplankton abundance for the decade showed a 10-fold range, from 1,575 – 18,278 ind. m^{-3} for the 150-µm mesh nets and 20-fold range,80.6 – 1,584 ind. m^{-3} for the 505-µm nets. Biomass had half these ranges, from 51.8 – 246.1 and 9.9 – 89.0 mg DW m^{-3} for the 150-µm and 505-µm nets, respectively. Despite large interannual variation, the overall trend was a decreasing abundance of major functional zooplankton groups captured with the 150-µm net across the ten-year time frame (Figure 11a). These decreasing trends were less noticeable or consistent in the larger size fraction captured with the 505-m net (Figure 11b).

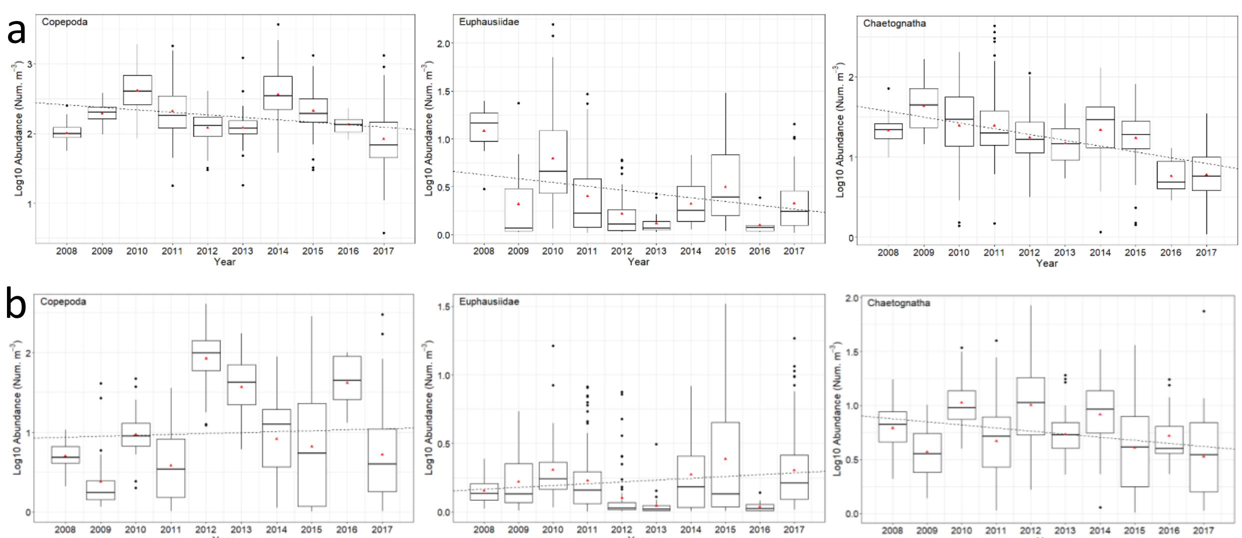

Fig. 11: Averaged abundance of larger zooplankton groups captured by the 150-µm mesh net (a) and the 550-µm mesh net (b) over the sampling years 2008-2017. The smaller size fraction shows a decreasing trend despite much interannual variability. This decrease was less consistent in the larger size fraction.

Changes in water masses subsequently altered the composition of the zooplankton communities tightly coupled to water types. In warm years coupled with early sea ice loss, WCW and WSW penetrated farther northward allowing Pacific expatriates (e.g., *Metridia pacifica*, and *Neocalanus* spp.) to dominate the system. Alternatively, cold years associated with prevalent sea ice cover resulted in slower water mass replacement, allowing larger lipid-rich Arctic species (e.g., *Calanus glacialis*) to thrive. For example, clustering of zooplankton community composition clearly shows different community compositions in the warm 2017 AMBON year compared to other years (Figure 12).

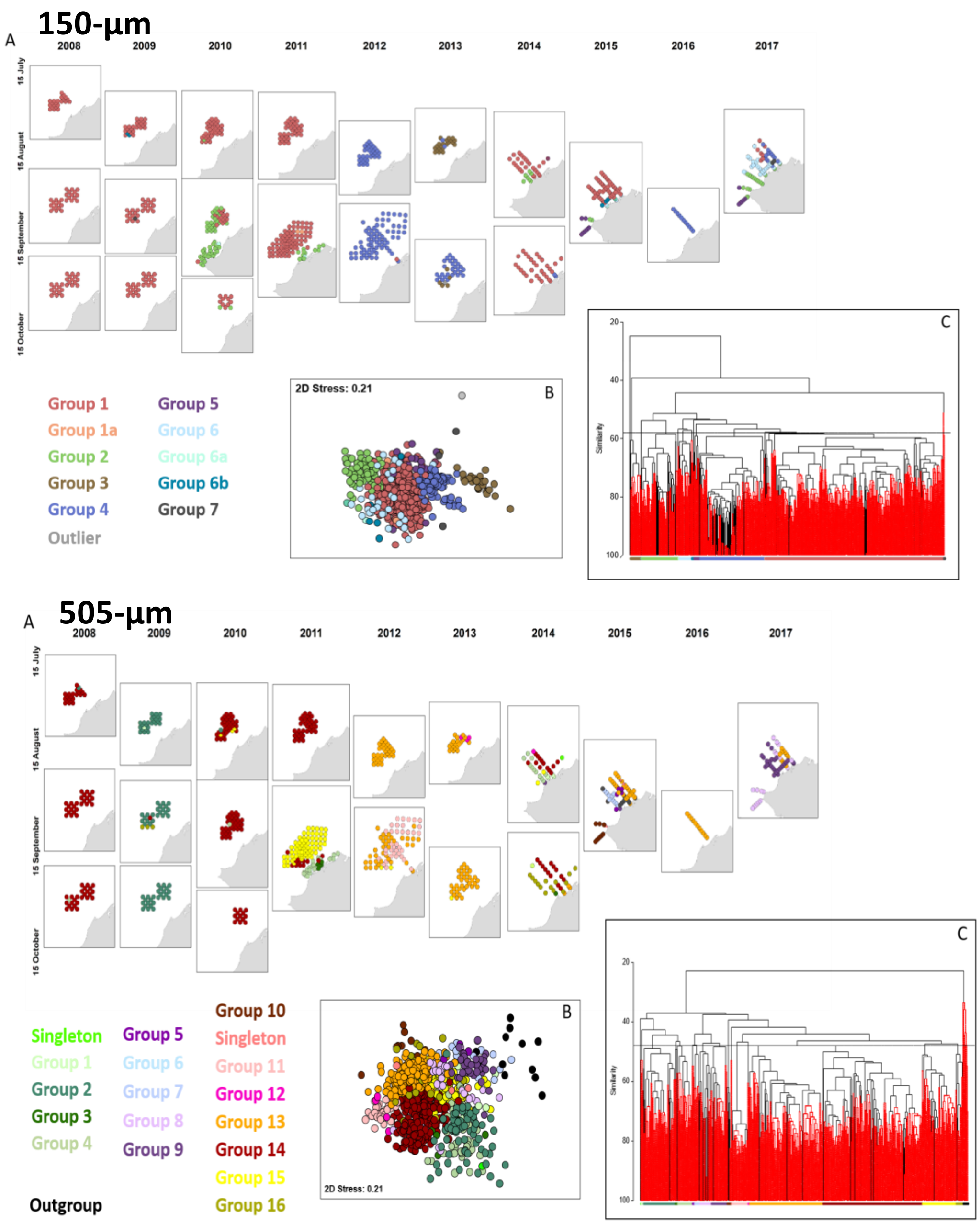

Fig. 12: Cluster analysis based on 150-µm and 505-µm abundance (ind. m^{-3}) data. For each net type, we show A) Spatial distribution of community groups B) Non-parametric Multidimensional Scaling (nMDS) of zooplankton community overlain with groupings. C) Hierarchical cluster dendrogram based on Bray-Curtis sample. Distinctly different and more variable community arrangements can be seen in later years that were warmer.

c. Comparison of Chukchi Sea meroplankton and benthic community

In addition to the general zooplankton community composition (Objective 2b), we also included AMBON plankton samples in an investigation of meroplankton distribution in relation to the distribution of benthic adult stages. Local benthic communities are fundamentally dependent on the larval supply, for example for replenishment after disturbances. The AMBON 2015 sample set complemented other meroplankton data from 2004, 2007, and 2009 so that interannual patterns could be determined. These patterns were then related to environmental measurements that were taken concurrently with the zooplankton tows so that water mass characteristics could be identified. The study found that spatial overlap between meroplanktonic and adult benthic occurrence was low, emphasizing the strongly advective nature of the Chukchi shelf and the long larval dispersal times, a result also found in the functional community assessment under Objective 1b (Sutton et al. 2020). This and the predominance of meroplankton of taxa not present as benthic adults in the region illustrated the probability of north-temperate species to successfully invade the Chukchi shelf through their larval dispersal once environmental conditions become more hospitable.

Published manuscript: **Appendix 13** of AMBON Final Report

Diversity and distribution of meroplanktonic larvae in the Pacific Arctic and connectivity with adult benthic invertebrate communities

Ershova, E.A., Descoteaux, R., Wangensteen, O.S., ***Iken, K., Hopcroft, R.R.,*** *Smoot, C.,* ***Grebmeier, J.M., Bluhm, B.A.*** 2019. *Frontiers in Marine Science*, *6*, p.490

Abstract

Pelagic larval stages (meroplankton) of benthic invertebrates seasonally make up a significant proportion of planktonic communities, as well as determine the distribution of their benthic adult stages, yet are frequently overlooked by both plankton and benthic studies. Within the Arctic, the role of meroplanktonic larvae may be particularly important in regions of inflow from sub-Arctic regions, where they can serve as vectors of advection of temperate species into the Arctic. In this study, we describe the links between the distribution of larvae and adult benthic communities of bivalves, echinoderms, select decapods and cnidarians on the Pacific-influenced Chukchi Sea shelf during August-September in the time period 2004–2015 using traditional morphological and molecular tools to resolve taxonomic diversity. For most taxa, we observed little regional overlap between the distribution of larvae and adults of the same taxon; however, larvae of some organisms (e.g., the burrowing anemone *Cerianthus* sp., the sand dollar *Echinarachnius parma*) were only observed near populations of adult organisms. Larval stages of species not commonly observed in the Chukchi Sea benthos were also observed in the plankton; overall, shelf meroplanktonic communities were numerically dominated by larvae of coastal hard-bottom taxa, rather than local soft-bottom shelf species. Our results suggest that most larvae that we observe on the shelf are advected from other areas rather than produced locally, and most likely will not successfully settle to the benthos. Seasonality and distribution of water masses were the most important parameters shaping meroplankton communities. We discuss the implications of changing oceanographic and climatic conditions on the potential of range extensions by temperate species into the Arctic Ocean.

d. Changes in seabird species composition in relation to warming conditions

AMBON data on seabirds were included in a long-term assemblage assessment and provided critical years of low and higher-ice cover data on seabird composition and distribution in relation to environmental conditions. During a period of record low ice and high water temperatures in the

Northern Bering and Chukchi seas (2017-2019), offshore distribution of seabirds changed from that of previous years (2012-1016). Seabird species richness declined in the Bering and southern Chukchi seas, but increased slightly in the northern Chukchi Sea. Overall, seabird abundance increased in the Chukchi Sea, mainly due to the increase in short-tailed shearwaters (*Ardenna tenuirostris*), which do not nest in Alaska, and are omnivorous but forage primarily on euphausiids while there. There was evidence of a decline in seabird abundance throughout the eastern North Bering – Chukchi LME, suggesting a westward shift as well as a northerly shift in distribution. Overall, observations suggest high food availability in the Chukchi Sea in recent years, or perhaps a relative abundance of prey, compared to the northern Bering Sea.

Published manuscript: **Appendix 14** of AMBON Final Report

Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming during 2017-2019

Kuletz, K., *Cushing, D., Labunski, D.* 2020. *Deep Sea Research II*, 181-182: 104913

Abstract

In the northern Bering Sea and eastern Chukchi Sea, 2017–2019 were record-breaking years for warm ocean temperatures and lack of sea ice. The region supports millions of seabirds that could be affected by shifts in prey distribution and availability caused by changing environmental drivers. However, seabirds are highly mobile and often flexible in diet, and might alter their foraging distributions accordingly. To determine if there was evidence of long-term changes in abundance of seabirds, or if seabirds used the offshore habitat differently during recent warm years, we compared species richness, community composition, and distribution and abundance of selected species and Total seabirds (all species combined) between two periods, 2007–2016 and 2017–2019. We also evaluated annual changes in abundance during 2007–2019. We used 79,426 km of transects from vessel-based surveys conducted July through September. Total seabird density for the entire study area increased by ~20% during 2017–2019, but changes were not consistent across the study area, nor among species, and species richness declined except for a slight increase in the northern Chukchi Sea. Total seabird density declined most in the northern Bering Sea (−27%), although it increased in the Chirikov Basin by 73%. During 2017–2019, abundance of piscivorous murres (*Uria* spp.) decreased everywhere, whereas planktivorous *Aethia* auklet density increased by 70% in Chirikov Basin; auklets apparently abandoned their post-breeding migration to the Chukchi Sea. Short-tailed shearwaters (*Ardenna tenuirostris*) expanded farther into the northern Chukchi Sea, with nearly twice the density of the previous decade. We identified five seabird community types, three of which (all dominated by an alcid species) contracted spatially in the later period, and shifted south or near colonies. In contrast, a short-tailed shearwater dominated community expanded northward, and a community defined by low seabird density expanded throughout the eastern portion of both the northern Bering and Chukchi seas, suggesting higher-density communities had shifted westward. The variable responses among species correspond to documented changes in the environment as well as their natural history.

e. Spatial patterns in Arctic cod in relation to environmental drivers

The open access AMBON data also contributed to an important large-scale assessment of key forage fish species in the Pacific Arctic. The Arctic cod is a central species in the Arctic food web, yet we still do not have a good understanding of its distribution across the ontogenetic development. Combining AMBON fish collections with those from a large number of other projects allowed a better understanding of how Arctic cod of different life stages distribute according to environmental conditions within the Pacific Arctic. Distribution of juvenile Arctic cod showed signs of population structure and different rearing habitats driven by temperature and salinity. Subadult and adult distribution was segregated and mostly driven by depth. The following publication is the result of a Master's thesis in Fisheries at the College of Fisheries and Ocean Sciences, UAF.

Published manuscript: **Appendix 15** of AMBON Final Report

Spatial patterns, environmental correlates, and potential seasonal migration triangle of polar cod (*Boreogadus saida*) distribution in the Chukchi and Beaufort seas

Forster, C.E., Norcross, B.L., ***Mueter, F.J.,*** *Logerwell, E.A., Seitz, A.C.* 2020. Polar Biology, 43: 1073–1094.

Abstract
Polar cod (*Boreogadus saida*) is a key forage fish in the Arctic marine ecosystem and provides an energetic link between lower and upper trophic levels. Despite its ecological importance, spatially explicit studies synthesizing polar cod distributions across research efforts have not previously been conducted in its Pacific range. We used spatial generalized additive models (GAMs) to map the distribution of polar cod by size class and relative to environmental variables. We compiled demersal trawl data from 21 cruises conducted during 2004–2017 in the Chukchi and Beaufort seas, and investigated size-specific patterns in distribution to infer movement ecology of polar cod as it develops from juvenile to adult life stages. High abundances of juvenile polar cod (≤70 mm) in the northeastern Chukchi Sea and western Beaufort Sea were separated from another region of high abundance in the eastern Beaufort Sea, near the US and Canadian border, suggesting possible population structure in the Pacific Arctic. Relating environmental correlates to polar cod abundance demonstrated that temperature and salinity were related to juvenile distribution patterns, while depth was the primary correlate of adult distribution. A comparison of seasonal 2017 abundances of polar cod in the southern Chukchi Sea found low demersal abundance in the spring when compared to the summer. Seasonal differences in polar cod abundance suggest that polar cod migration may follow a classical 'migration triangle' route between nursery grounds as juveniles, feeding grounds as subadults, and spawning grounds as adults, in relation to ice cover and seasonal production in the Chukchi Sea.

f. Hatch dates and growth rates of Arctic cod

Similar to Objective 2e, AMBON catch data also contributed to an analysis of hatch dates and growth rates of first-year Arctic cod to better understand ontogenetic distribution and population dynamics of this key species. We found that Arctic cod employ a bet-hatching strategy where hatch date is spread out over several months so that larvae have a higher chance of survival in the highly variable Arctic conditions. The following draft manuscript is the result of a Master's thesis in Fisheries at the College of Fisheries and Ocean Sciences, UAF.

Draft manuscript in preparation for submission: **Appendix 16** of AMBON Final Report

Otolith-derived hatch dates and growth rates of Arctic cod (*Boreogadus saida*) support existence of several spawning populations in Alaskan waters

Chapman, Z., ***Mueter, F.J.,*** *Norcross, B.L., Oxman, D.S.* in preparation for *Deep Sea Research II.*

Abstract
Arctic cod are an important prey species in Arctic marine ecosystems as they provide efficient energy transfer up the food web. They are found throughout the Arctic and have locally high abundances. Little is known about the early life of Arctic cod in the Pacific Arctic, such as when and where they spawn and hatch, but they are known to have a close relationship with sea ice during incubation and may associate with sea ice through much of their early life history. The goal of this study was to use daily ages determined from otolith growth increments to estimate hatch dates and growth rates of first year Arctic cod. Samples were captured in the northern Bering, Chukchi, and Beaufort seas during the spring or summer between 2012 and 2017. Estimated hatch dates ranged widely from November to July with peak hatch dates occurring from February through May depending on the region of capture. Combined with large individual and

regional variability in growth rates, this suggests a bet-hedging strategy to ensures that at least some larvae encounter favorable growth conditions. In addition to regional differences, we identified a clear separation of hatch dates between spring- and summer-caught Arctic cod, suggesting different origins or strong size-dependent mortality. Finally, differences in hatch dates between pelagic and demersal juveniles support the settlement of older, larger juveniles to the seafloor on deeper portions of the shelf. Interpreting differences in hatch timing and growth in the context of variability in sea ice retreat, river discharge and other environmental conditions can provide new insights into the future of Arctic cod as the Arctic climate continues to change.

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g. Interactions of early life stages of Arctic and Saffron cod

The early life history of forage fishes in the Arctic is a fundamental knowledge gap in Arctic ecosystem functioning. In addition, juveniles of species with similar ecological niches compete for resources in the system. AMBON fish catch and length-frequency data were used to better understand the distribution and growth of juvenile Arctic cod and Saffron cod in the Pacific Arctic to understand their interactions in the specific environment.

Manuscript in revision: **Appendix 17** of AMBON Final Report

Seasonal abundance, distribution, and growth of the early life stages of Polar Cod (*Boreogadus saida*) and Saffron Cod (*Eleginus gracilis*) in the US Arctic during a warm year

Deary, A.L., Vestfals, C.D., Logerwell, E.A., Goldstein, E.D., Stabeno, P.J., ***Danielson, S.L., Mueter, F.J.,*** *Duffy-Anderson, J.T.* In revision at *Polar Biology*

Abstract

Polar Cod and Saffron Cod are dominant components of the fish community in the Chukchi Sea and are ecologically important forage fishes linking plankton to upper level consumers. In 2017, we conducted a study as part of the Arctic Integrated Ecosystem Research Program to characterize the distribution, abundance, and growth of Polar Cod and Saffron Cod early life history stages (ELHS) in late spring and late summer in the Chukchi Sea. Ship-based plankton tows showed that Polar Cod and Saffron Cod larvae were centered in Kotzebue Sound in the late spring. By late summer, Polar Cod juveniles were centered offshore in the northern Chukchi Sea whereas Saffron Cod were distributed nearshore around Cape Lisburne. Empirical fish collections were paired with an individual-based biophysical transport model to examine connectivity and relate changes in seasonal distribution to potential environmental variables. Modeled drift trajectories and growth in spring for Polar Cod and Saffron Cod matched well with empirical observations, especially along the northern coastline of Kotzebue Sound, offshore of Point Hope/Cape Lisburne. Given the coherence between modeled and observed distributions, Kotzebue Sound is likely a source of gadid ELHS in the nearshore areas of the Chukchi Sea and offshore of Cape Lisburne/Point Hope, although it is not the likely source of Polar Cod over Hanna Shoal in the late summer. This is the first study to examine seasonal distribution, abundance, and growth of Polar Cod and Saffron Cod in the US Arctic, and provides data necessary to evaluate the impacts of climate change on forage fishes in the Arctic.

h. Summer distribution of adult Arctic and Saffron cod

In an extension to Objective 2g, we also used AMBON size-frequency distribution data to assess juvenile and adult distribution of Arctic cod and Saffron cod. This is not only important ecologically but also for management considerations as the Arctic is an area of interest for future fisheries expansion. To be able to determine the viability of commercial fisheries activities in the Arctic, the standing stock and sensitivity to biomass removal needs to be determined. This is an excellent example in how AMBON data are contributing to the management of marine resources.

Manuscript in preparation:

Shifting summer distributions of Arctic cod (*Boreogadus saida*) and saffron cod (*Eleginus gracilis*) in the Alaskan Arctic

Marsh, J.M., ***Mueter, F.J.,*** *Pirtle, J.*

Preliminary Abstract: The climate and oceans are rapidly warming in the Alaskan Arctic, with far reaching impacts on marine ecosystems, including fishes. As key prey items for many marine mammals and seabirds, Arctic cod and saffron cod are two of the most ecologically important fishes within the Alaskan Arctic. Additionally, both are harvested in subsistence fisheries and have been identified as two of three potential targets for commercial fisheries in the Arctic Management Area by the North Pacific Fishery Management Council. Currently, little is known about the response of these fish to warming in the Chukchi and Beaufort seas. We used environmental and biological survey data from 2000 - 2018 to model the distribution of juvenile and mature Arctic cod and saffron cod during warm and cold periods, respectively, in the US Chukchi and Beaufort seas. These species distribution models identify key habitat characteristics and define habitat suitability for these species in the Alaskan Arctic during contrasting warm and cold years. Observed shifts between modeled distributions in response to changing temperatures may provide insight into future shifts in distribution with climate change.

i. New population dynamic parameters of Alaskan Arctic snow crab

Management considerations do not only apply to fin fish but also other species of fisheries interest. In the Arctic these include scow crab. This valuable commercial resource in the Bering Sea seems to contract their current distribution northward towards the Arctic due to climate warming, diminishing the current fisheries returns in the Bering Sea. Snow crab are a common member of the epibenthic community on the Chukchi shelf, but the 2009 Arctic Fisheries Management Plan, based on a very limited Arctic dataset, determined that commercial extraction was not viable at the time in the Arctic. With diminishing catches in other regions, there is an urgent need to reassess the Plan and expand the information base. The large spatial coverage and the unprecedented large dataset of crab size-frequency distribution measured during the AMBON project allowed us to contribute to a new stock assessment of snow crab in the Chukchi Sea.

Published manuscript: **Appendix 18** of AMBON Final Report

New estimates of weight-at-size, maturity-at-size, fecundity, and biomass of snow crab, *Chionoecetes opilio*, in the Arctic Ocean off Alaska

Divine, L.M., ***Mueter, F.J.,*** *Kruse, G.H.,* ***Bluhm, B.A.,*** *Jewett, S.C.,* ***Iken, K.,*** 2019. *Fisheries Research*, *218*: 246-258.

Abstract

Snow crab (*Chionoecetes opilio*) were identified as a potential future target fishery species in federal waters of the Arctic Ocean off Alaska by the Arctic Fishery Management Plan (Arctic FMP) in 2009, but this plan currently prohibits commercial harvest until sufficient information is available to assess a sustainable commercial fishery. One drawback of the current Arctic FMP is that critical population and biomass estimates were based on limited data. Collaborative research efforts in the Chukchi and Beaufort seas over the past decade have yielded a much richer database on snow crab in the Arctic. Using these data, we generated new estimates of weight-at-size, maturity-at-size, fecundity, and biomass to recalculate sustainable yield of snow crab in the U.S. Arctic. Weight-at-size was generally similar for male and female snow crab between the Chukchi and Beaufort seas, with males reaching overall larger sizes than females in both seas and largest male crabs occurring in the Beaufort Sea. Compared with snow crab in other geographic regions, 50% morphometric maturity was reached at a slightly smaller size in the Chukchi Sea; low sample sizes in the Beaufort Sea prevented maturity-at-size analysis. Fecundity-at-size in the Chukchi Sea was similar to known values estimated for snow crab in other regions. Estimated total reproductive output, using fecundity estimates obtained here, suggest that local reproduction may be sufficient to account for a large portion of observed small juvenile benthic snow crab abundances; further investigation is warranted to determine whether Chukchi and Beaufort populations are self-sustaining at this time. Although snow crab had high abundances in the Chukchi Sea, harvestable biomass of male snow crab only occurred in the Beaufort Sea because crab larger than the minimum marketable size (≥ 100 mm carapace width, based on Bering Sea metric) were absent in the Chukchi Sea over the study period. Our biomass estimates in the Chukchi Sea were substantially higher than previous estimates, owing at least in part to high abundances of small crab that were greatly under-sampled with the large-mesh gear such as was used in surveys referenced in the Arctic FMP. Estimates of biomass and sustainable yield for the Beaufort Sea were over twice as high as previous estimates in the Arctic FMP, but harvestable biomass was largely limited to the slope (> 200 m depth) and is unlikely to support commercial harvest. Our results expand overall understanding of arctic snow crab dynamics in light of potential future fisheries or other, non-fishing activities and inform the management of the Alaskan Arctic stock.

j. Year-round patters in phytoplankton in the northern Chukchi Sea

In a collaborative approach with other ongoing programs, we explored the possibility to determine year-round phytoplankton diversity from sediment trap samples. Unsurprisingly, diatoms were the best-preserved taxa but those could be identified at high taxonomic accuracy. The sequential shifts in peak abundances of different taxa were a clear indicator of environmental changes, such as the onset of sea ice cover melt. These results show that while the full phytoplanktonic biodiversity spectrum including flagellates may be difficult to discern from such samples, this is a valuable approach to garner insight into the timing of biodiversity shifts that are indicative of ecosystem processes. This is a considerable extension from the usual particle/carbon flux measurements derived from sediment trap samples. Especially in a system like the Arctic where sampling access is typically limited to a single annual event, this approach can provide essential biological information about seasonal processes at the base of the food web.

Published manuscript: **Appendix 19** of AMBON Final Report

Annual cycle of export fluxes of biogenic matter near Hanna Shoal in the northeast Chukchi Sea

Lalande C, ***Grebmeier JM, Hopcroft RR, Danielson SL****.* 2020. *Deep-Sea Research II* 177: 104730

Abstract
The Chukchi Ecosystem Observatory (CEO), a mooring array of subsurface oceanographic instruments, was established on the northeast Chukchi Sea continental shelf to obtain time-series measurements of physical, biogeochemical, and biological parameters. A sequential sediment trap was deployed on a CEO mooring 8 m above seafloor to measure export fluxes of chlorophyll a (chl a), microalgal cells, zooplankton fecal pellets, total particulate matter (TPM), particulate organic carbon (POC), and zooplankton actively entering the trap from August 2015 to July 2016. These time-series measurements allowed us to monitor sympagic and pelagic algal production, the seasonal development of the zooplankton community, pelagic-benthic coupling, and particulate matter export in relation to snow and sea-ice cover on the shallow Chukchi Sea continental shelf. Notably, chl a and algal fluxes were nearly as high from August to October 2015 as in June–July 2016, indicating substantial autumn production. Autumn algal fluxes were dominated by the epipelic *Cylindrotheca closterium* while summer fluxes were dominated by pennate diatoms, including *Fossula arctica* and *Neodenticula seminae*. Peaks in the export of the exclusively sympagic diatom *Nitzschia frigida* in May and June 2016 indicated the release of ice algae due to snow and ice melt events. While pelagic copepods *Calanus glacialis/marshallae*, *Pseudocalanus* spp. and *Oithona similis* were the dominant

copepods collected in the sediment trap, meroplanktonic stages of benthic organisms displayed the largest abundances and reflected mixing of pelagic stages and resuspension events on the shallow Chukchi Sea shelf. Enhanced fecal pellet carbon fluxes reflected zooplankton grazing in August and September 2015 and in July 2016. Despite the grazing pressure, high chl a, diatom and POC fluxes during these periods allowed strong pelagic-benthic coupling in the northeast Chukchi Sea. Persistent summer and autumn production also suggest that the local benthic community benefits from a sustained food supply rather than episodic flux events. Overall, these observations demonstrate the importance of year-round monitoring for fully understanding the phenology of marine processes and set a baseline for understanding the impact of environmental changes on Arctic marine ecosystems.

k. Potential transformation and tipping point of the Pacific Arctic

AMBON data contributed to a high-level synthesis of ecosystem changes in the Pacific Arctic in response to environmental conditions. While the Arctic has experienced increasing sea ice loss and warming and freshening conditions in recent years, conditions since 2017 in environment and biological conditions have changed in a way that could suggest the system may have reached a tipping point. AMBON sampling in 2017 was critical for this analysis as this was one of the years that allowed us to determine the tipping point dynamics. The manuscript was published in the top-ranking journal *Nature Climate Change*.

Published manuscript: **Appendix 20** of AMBON Final Report

Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway

*Huntington HP, **Danielson SL,** Wiese FK, Baker M, Boveng P, Citta JJ, De Robertis A, Dickson DM, Farley E, George JC, **Iken K,** Kimmel DG, **Kuletz K,** Ladd C, Levine R, Quakenbush L, Stabeno P, **Stafford KM**, Stockwell D, Wilson C*. 2020. *Nature Climate Change* 10(4): 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 that this change of state 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.

Objective 3: To demonstrate at a regional level how a MBON could be developed in other regions and ecosystems

One focus of the AMBON project was to assess a useful, sustainable and representative design of a regional Marine Biodiversity Observing Network in the Chukchi Sea. Specifically, data collection in the Arctic is highly restricted because of climate (sea ice cover over much of the year, adverse weather conditions), logistics (only few vessels are able to operate in the Arctic), and finances (vessel costs are very high). Hence, using the AMBON dataset for different model exercises to assess the robustness of various designs of monitoring sampling for different ecosystem components was ideal to develop the most cost-effective strategies at a minimal loss of information and power of detection.

a. Observational design considerations

The Arctic shelf system is considered a benthic-dominated system because much of the primary production from the ice-associated and pelagic system sinks ungrazed to the seafloor, resulting in high benthic biomass and biodiversity. Benthic assessments are time and labor intensive, so understanding the spatial scale of sampling necessary to detect patterns in benthic community composition and biodiversity is important. We found that reducing the spatial sampling scale from the full AMBON coverage resulted in a significant loss of benthic invertebrate biodiversity although this loss was less severe for demersal fish. We found that maintaining sampling lines that cover the entire cross-shelf direction is important but the number of these transect lines could possibly be reduced.

Published manuscript: **Appendix 21** of AMBON Final Report

Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea

Iken K, Mueter FJ, Grebmeier J, Cooper L, Danielson SL, Bluhm B. 2019. *Deep-Sea Research II* 162: 180-190.

Abstract
In light of ongoing, and accelerating, environmental changes in the Pacific sector of the Arctic Ocean, the ability to track subsequent changes over time in various marine ecosystem components has become a major research goal. The high logistical efforts and costs associated with arctic work demand the prudent use of existing resources for the most comprehensive information gain. Here, we compare the information that can be gained for epibenthic invertebrate and for demersal fish assemblages reflecting coverage on two different spatial scales: a broader spatial coverage from the Arctic Marine Biodiversity Observing Network (AMBON, 67 stations total), and the spatial coverage from a subset of these stations (14 stations) that reflect two standard transect lines of the Distributed Biological Observatory (DBO). Multivariate cluster analysis was used to discern community similarity patterns in epibenthic invertebrate and fish communities. The 14 stations reflecting the two DBO lines captured about 57% of the epibenthic species richness that was observed through the larger-scale AMBON coverage, with a higher percentage on the more southern DBO3 than the northern DBO4 line. For demersal fishes, both DBO lines captured 88% of the richness from the larger AMBON spatial coverage. The epifaunal assemblage clustered along the south-north and the inshore-offshore axes of the overall study region. Of these, the southern DBO3 line well represented the regional (southern) epifaunal assemblage structure, while the northern DBO4 line only captured a small number of the distinct assemblage clusters. The demersal fish assemblage displayed little spatial structure with only one coastal and one offshore cluster. Again, this structure was well represented by the southern DBO3 line but less by the northern DBO4 line. We propose that extending the coverage of the DBO4 line in the northern Chukchi Sea farther inshore and offshore would result in better representation of the overall northern Chukchi epifaunal and fish assemblages. In addition, the multi-annual stability of epifaunal and, to a lesser extent also fish assemblages, suggests that these components may not need to be sampled on an annual basis and sampling every 2–3 years could still provide sufficient understanding of long-term changes. Sampling these assemblages every few years from a larger region such as covered by the AMBON project would create the larger-scale context that is important in spatial planning of long-term observing.

b. Trade-offs among sampling designs across ecosystem components

Aside from optimizing biodiversity sampling for individual ecosystem components (Objective 2a, c), we are also developing a simulation approach to compare diversity measures across multiple components. Specifically, we used the across- and alongshore transect design of the AMBON project and the grid design of a corresponding project to systematically assess the effect of removing the density of transects or of stations on the power of detection of community change from rare (e.g., invasive) species. We have so far tested the computationally intense modeling approach for demersal fish; in a next step will include the other ecosystem components. We found that uncertainty of biodiversity assessments was fairly robust even at decreased station coverage for common species but that the power to detect changes in rare species decreased significantly with a smaller sampling coverage. This modeling approach allows us to optimize biodiversity sampling within the limited time and funding frameworks in the Chukchi Sea; however, the general approach of modeling the efficiency, accuracy and biases of biodiversity monitoring designs is one that can be employed in other regions and can assist with the development of a national MBON.

Manuscript in preparation: **Appendix 22** of AMBON Final Report

Trade-offs among sampling designs for monitoring biodiversity and abundance of marine organisms in the Chukchi Sea

Mueter, F.J., Iken, K., *Cooper, D.,* ***Grebmeier, J., Hopcroft, R., Kuletz, K, Danielson, S.*** In preparation for submission to *PLoS One*.

Abstract
Assessing and quantifying biodiversity at multiple levels is a key component of monitoring and understanding changes in marine ecosystems. Adequate monitoring is particularly challenging in remote, high-latitude regions such as the Chukchi Sea, an Arctic inflow shelf that is undergoing rapid environmental changes. Current monitoring efforts in the Chukchi Sea rely on opportunistic sampling in recognized 'hot spots' (the Distributed Biological Observatory, DBO) or dedicated, but typically short-term, monitoring programs. The relatively extensive sampling design used during Arctic Marine Biodiversity Observing Network (AMBON) surveys in the northeast Chukchi Sea in 2015 and 2017 and by the Arctic Integrated Ecosystem Survey (AEIS) in 2017 provide an opportunity to evaluate the effectiveness of different sampling designs for quantifying biodiversity. We evaluated how common diversity measures and their uncertainty vary across a set of reduced survey designs that were pragmatic subsets of the stations sampled by the full AMBON and AIES designs. As a case study, we estimated the power to detect changes in diversity of the demersal fish community resulting from the expansion of new or rare species into the study region. A framework was developed to simulate changes from the 2017 baseline using temperature-dependent changes in the probability of occurrence of new or otherwise undetected species. Results suggest no apparent bias in diversity estimates for any of the reduced designs, including those with spatially restricted sampling such as the Distributed Biological Observatory (DBO), but substantial increases in uncertainty as sample sizes decrease. This high uncertainty contributed to the poor performance of most sampling designs in terms of detecting changes in the presence of relatively rare species from baseline conditions. Our study provides a general framework for evaluating alternative sampling designs in the context of monitoring biodiversity that can easily be adapted to other regions and communities and can be used to test a variety of hypotheses about the nature of possible changes.

C. Monitoring design for seabirds

AMBON data on seabirds were included in a manuscript that investigated if a subset of a large spatial cover such as through AMBON can reasonably describe and monitor seabird abundance in the eastern Pacific Arctic. Datasets from multiple study projects were included. Species richness (totaling 63 species) was highest in the Bering Sea, intermediate in the Chukchi Sea, and lowest in the Beaufort Sea. Assessing result at the reduced spatial scale of the Distributed Biological Observatory (DBO) coverage, species diversity indices were similar among most DBO sites and regions. Total seabird abundance was highest in and near Bering Strait, and declined steeply northward and eastward of Point Barrow. Six seabird community types were identified in the area, five of which occurred in the

AMBON study area. The consistency in species' abundance by DBO site indicates that the DBO will be useful for monitoring seabirds in each region, although long-distance migrants (shearwaters, murrelets) showed higher interannual variability and may be better monitored with a larger sampling design such as the AMBON.

Published manuscript: **Appendix 23** of AMBON Final Report

Representation of the Pacific Arctic seabird community within the Distributed Biological Observatory array, 2007-2015.

Kuletz, K., *D. A. Cushing, E.E. Osnas, E.A. Labunski, A.E. Gall.* 2019. *Deep Sea Research II* 162:191-210.

Abstract
An array of eight Distributed Biological Observatory (DBO) sites serve as long-term monitoring areas for three geographic regions: the northern Bering, eastern Chukchi, and Beaufort seas. The locations of the DBO sites were largely determined based on abundance and diversity of benthic invertebrates. It is not clear how well these fixed sampling sites can detect changes in processes and populations that operate over spatial scales that are 1–3 orders of magnitude greater than the areas sampled by the DBO sites. In this paper, we examine whether the DBO array provides a reasonable method by which to describe and monitor the distribution and community composition of seabirds in the eastern Pacific Arctic, and if it captures areas of high seabird abundance. We used vessel-based survey data totaling ~115,860 km of transects within the study area from July–October 2007–2015. We compared species richness, diversity, abundance, and community composition of seabirds among DBO sites and to the broader geographic regions. In general, the avifauna of DBO sites were representative of their respective surrounding region, although sampling effort in the Beaufort was limited. Species richness (totaling 63 species) was highest in the Bering region and lowest in the Beaufort region. Species diversity indices were similar among DBO sites and regions, except for exceptionally low diversity in the two easternmost DBO sites of the Beaufort region. Total seabird abundance was highest in and near Bering Strait, and dropped abruptly northward and eastward of Point Barrow. We used K-means cluster analysis to identify six community types across the entire study area, with five community types identified as having at least one numerically dominant species, and one community type defined by very low densities of a variety of species. Several community types were associated with major current systems (e.g. Anadyr Current, Alaska Coastal Current), and for two community types, breeding colony locations were also influential. Short-tailed shearwaters were the most abundant species in five of the eight DBO sites, and they were the numerically dominant species in a community that was represented from DBO 1 through DBO 6. Overall, variance in abundance was much greater by DBO site (or region) than by year for total birds and for seven of eleven taxa. Taxa with greater interannual variance than spatial variance were shearwaters and phalaropes (among regions), and murrelets (among DBO sites), all of which are late summer migrants to the study area, and glaucous gulls, a circumpolar species. The consistency in species' abundance by site indicates that DBO sites will be useful for monitoring seabirds in each region. As an array, the DBO sites captured major hotspots of seabird abundance as well as the seabird communities, except for the fulmar-dominated community in the outer Bering Shelf. However, all DBO sites will need to be surveyed to capture the full range of seabird communities in this study area. The Beaufort DBO sites require more survey coverage than currently achieved to fully evaluate their effectiveness to monitor changes in seabirds for that region.

d. Collaborative approaches of multiple observing systems

Ecosystem observing systems can be designed in a variety of manners. In the Chukchi Sea, several observing systems operate simultaneously, each designed under a different set of priorities. The Chukchi Ecosystem Observatory is a moored system that collects biological and environmental information year-round in a fixed location. The Distributed Biological Observatory focuses on specific regions that are considered "hotspots" of biological production. The Arctic Marine Biodiversity

Observing Network (AMBON) employs an approach that covers a large shelf area to capture biodiversity across the entire environmental conditions on the shelf. Each of these programs has benefits and shortcomings. Here we explore these together in how such systems can be complementary, depending on the questions being asked.

Published manuscript: **Appendix 24** of AMBON Final Report

Collaborative approaches to multi-disciplinary monitoring of the Chukchi shelf marine ecosystem: Networks of networks for maintaining long-term Arctic observations

Danielson, S.L., Iken, K., *Hauri, C.,* ***Hopcroft, R.R.,*** *McDonnell, A.M., Winsor, P., Lalande, C.,* ***Grebmeier, J.M., Cooper, L.W.,*** *Horne, J.K.* ***Stafford, K.M.,*** 2017, September. In *OCEANS 2017-Anchorage* (pp. 1-7). IEEE.

Abstract
In 2015, the Hanna Shoal region of the Chukchi Sea shallower than the 40 m isobath was withdrawn from outer continental shelf oil and gas exploration, a move the White House noted was designed to protect areas of "critical importance … for marine mammals, other wildlife, and wildlife habitat". Arctic regions are projected to strongly manifest impacts of an altered climate and subsurface moored continuous observations are essential for understanding time-dependent marine processes that are likely to change in unanticipated ways. However, autonomous observations in this cold, ice-covered, and corrosive environment are difficult operations. Since 2014, the moored Chukchi Ecosystem Observatory (CEO) has been located in 45 m of water on the southern flank of Hanna Shoal just a few kilometers south of the marine protected area boundary. Concurrent measurements include physical, nutrient and carbonate chemistry, particulate, phytoplankton, zooplankton, fisheries, and marine mammal data sets. These measurements provide a unique multi-disciplinary view into the mechanistic workings of the Chukchi shelf ecosystem. Ship-based programs including the Arctic Marine Biodiversity Observation Network (AMBON) and the Distributed Biological Observatory (DBO) place the CEO within a broader spatial context of observations and provide vessel support for mooring recoveries and deployments, as well as visual marine mammal and marine bird surveys and both water column and benthic biological measurements. In turn, the CEO helps anchor the AMBON and DBO data in time with long duration and high temporal resolution sampling.
The technology and the collaborative approach associated with AMBON, the CEO, and the DBO are leading to sustained observations that are expanding our ability to understand seasonality of physical, biochemical, and biological processes on Arctic shelves. These sustained observations are examining processes that contribute to short (seconds) and long (years) time scale variations, and the reasons that Hanna Shoal is of particular importance to walrus and other wildlife. Together, these programs' observations reveal consequences of wind and wave activity on ocean currents and water column hydrography, the annual cycle of nutrient draw-down and replenishment, the timing and composition of particulate matter settling, the status of lower trophic level biological communities, marine mammal activity, the distribution of ice keels, and the timing and location of fish and macrozooplankton in the water column. Such measurements are helping guide a better understanding of the ecological functioning of the biologically-rich Hanna Shoal region.

Objective 4: To link with programs on the national and pan-Arctic level

The AMBON project is part of, and contributes to, a network of other projects, specifically on the pan-Arctic level, as well as nationally with other MBON projects. These international and national linkages provide opportunities to share research results with a wide variety of endusers, from other scientists, the public and indigenous communities, national resource managers, to intergovernmental forums such as the Arctic Council and its Senior Arctic Officials.

a. Circumpolar Biodiversity Monitoring Program (CBMP)

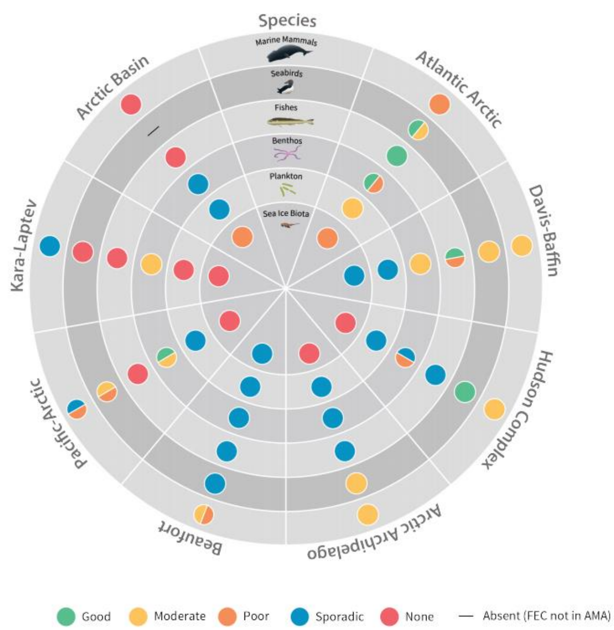
Several AMBON PIs are members of the Circumpolar Biodiversity Monitoring Program (CBMP), a program within the Circumpolar Flora and Fauna (CAFF) Working Group of the Arctic Council. The goal of the CBMP is to coordinate and harmonize long-term biodiversity monitoring efforts on a pan-Arctic level and across all ecosystem components. The AMBON project features prominently in the US contributions to the CBMP as the broad scale and the ecosystem-wide scale of biodiversity observations within AMBON match well the goals of the CBMP. One example of a large effort within the CBMP that occurred during the period of performance of the AMBON project and to which AMBON contributed significantly was the State of the Arctic Marine Biodiversity Report (SAMBR). This document synthesizes existing information and identifies gaps in knowledge in Arctic biodiversity. The report is being used by the different Arctic countries, including the US, to help design, continue or initiate biodiversity observing.

SAMBR: **Appendix 25** of AMBON Final Report

State of the Arctic Marine Biodiversity Report

Contributing AMBON PI authors to the SAMBR: ***B. Bluhm, R. Hopcroft, K. Iken, K. Kuletz***

Presented here is a summary figure of the SAMBR, showing the status of monitoring activities for each Focal Ecosystem Component (i.e., selected species groups) across different marine ecosystem regions.



b. Circumpolar Seabird Expert Network (CBird)

The Circumpolar Seabird Expert Network (CBird), one of the specific CBMP Expert Networks, regularly makes country update contributions to CAFF. The 2020 USA country update for CBird for

2020 specifically outlines AMBON as one of the key projects in the US that produces seabird information that contributes to our pan-Arctic understanding.

CBird U.S.A., 2020: **Appendix 26** of AMBON Final Report

Circumpolar Seabird Expert Group (CBird) Implementation Update U.S.A., 2020

Contributing AMBON PI: ***Kuletz K***

C. Integrated Ecosystem Assessments (IEA)

AMBON PIs are engaged in Integrated Ecosystem Assessments (IEA) for Arctic regions, an important international framework to provide ecosystem-integrated information to decision-making resource managers. IEA are being developed for multiple Arctic regions; the one for the Central Arctic Ocean occurred during the duration of the AMBON project. Concerns for the Central Arctic Ocean include increasing ship traffic due to reduced sea ice cover, an increased risk of oil spills, pollution from microplastics, potential future fisheries (although an agreement has been made to ban commercial fishing in the high seas), and the associated loss of biodiversity. The IEA for the Central Arctic Ocean was published in 2020, with contributions from several AMBON PIs (*Bluhm B, Grebmeier J, Kuletz K*).

Similarly, AMBON PIs are currently involved in a newly initiated IEA for the Northern Bering Sea and the Chukchi Sea; this initiative has only just begun and has been formally accepted as PICES Working Group 44. Contributing AMBON PIs are: *Cooper L, Iken K, Kuletz K*

WGICA 2020: **Appendix 27** of AMBON Final Report

ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA)

Bengtson et al. with contributing AMBON PIs: ***Bluhm, B, Grebmeier J, Kuletz K.*** 2020. ICES Scientific Reports. 2:79. 144 pp. http://doi.org/10.17895/ices.pub.7454

Abstract
The Working Group on the Integrated Assessment of the Central Arctic Ocean (WGICA) aims to provide a holistic analysis of the present and future status of the ecosystem and human activities therein. Data collection in the Central Arctic Ocean (CAO) has been inconsistent both spatially and temporally, which can limit the ability to conduct comprehensive analyses of trends and warning signals. However, coverage of data collection has been improving over the past few years. WGICA collates and analyses this regional information, which will be used to help guide the production of an Ecosystem Overview (EO) that relates the main regional pressures in the CAO with the human activities and the ecosystem components that are most impacted by these pressures. Climate change reduces sea ice, increases light penetration, causes regionally variable trends in stratification and mixing of the water column, increases inflow in both the Atlantic and Pacific sectors, and heating of waters at the surface and extending deeper and deeper. These changes in turn affect primary production and cascade through the food web to ice-associated fauna, zooplankton, fish, benthos, and sea mammals. These changes may be exacerbated by increasing human activities in and around the CAO, including increasing pollution from ship traffic and from the transport of contaminants to the ecoregion by rivers and ocean currents. The number of ships and distances traveled are increasing and it is anticipated that both commercial and tourist traffic by sea and air will continue to rise. The CAO has become an important sink for many pollutants such as microplastics, which have been found in sea ice and wildlife. Current and future threats to the ecoregion from these activities also include increased risk of oil spills and biodiversity loss if ocean mining expands into the Arctic. While an agreement has been made to ban commercial

fishing in the high seas of the Central Arctic Ocean; fish populations continue to be impacted by the effects of a warming ocean, retreating ice-cover and acidification. These threats have important ecological and policy implications for the entire food web and the Arctic community. For example, negative impacts on the polar cod population will negatively impact ringed seals and beluga whales and therefore will also affect subsistence harvests in the future. In upcoming years, WGICA plans to further define and describe human activities and resulting pressures and related management organizations, and develop a climate and vulnerability assessment of the CAO.

d. Pacific Arctic Group (PAG) and the Ecosystem Studies of the Subarctic and Arctic Seas (ESSAS)

Other international Arctic groups that AMBON PIs are involved in are the Pacific Arctic Group (PAG) and the Ecosystem Studies of the Subarctic and Arctic Seas (ESSAS). The PAG is a group of scientists and institutions, organized under the International Arctic Science Committee (IASC), that collaborates on the coordination of scientific activities in the Pacific Arctic regions. These collaborations include the coordination of national science activities, data sharing, and joint identification of science gaps. Several AMBON PIs have key roles in leading the PAG (e.g., *J. Grebmeier and L. Cooper*), but almost all AMBON PIs participate in the PAG planning and information meetings. On a pan-Arctic scale, AMBON is also linked to the ESSAS program, which has been co-chaired by AMBON Co-PI *F. Mueter* since 2011, along with B. Planque (IMR, Norway) and N. Harada (JAMSTEC, Japan). ESSAS is a regional (Arctic) program under the Integrated Marine Biosphere Research (IMBeR) program and its main goal is to understand the impacts of climate variability on Subarctic and Arctic marine ecosystems. To this end, ESSAS coordinates and actively fosters comparative analyses on the effects of climate variability and climate change on these ecosystems, with a special focus on the transition zones between the Subarctic and Arctic. It brings together researchers from its member countries to participate in workshops, scientific sessions and periodic Open Science Meetings. The AMBON project was endorsed by ESSAS in 2014 and AMBON science has informed comparative analyses between the Pacific and Atlantic gateways (Thorson et al. 2019, Marsh and Mueter 2020, Mueter et al., in review). AMBON science is regularly shared with the community of 60-100 scientists from around the circumpolar North that attend the ESSAS annual meetings and the data and findings from AMBON continue to contribute to ongoing comparative efforts.

e. xMBON

The AMBON project was one of several “Initiating a national MBON” projects, and the interaction with other MBONs was essential to identify shared elements of the network projects that would become an essential part of a national MBON framework. One of the issues with the development of a unified national MBON is that marine systems of national interest or concern are vastly different in their structure (e.g., coastal systems defined by biogenic foundation systems vs. continental shelf systems), dynamics (spatial and temporal scales of variation that critically influence ecosystem processes that determine the biodiversity sampling design), and logistics (some systems are easily accessible on a daily basis while others are only accessible on an annual basis at great cost). It has been recognized that the inherent differences in systems and logistical constraints, as well as consistency with historical, long-term data streams, prevent that every marine system would be monitored and sampled in the exact same way. Hence, sharing the structure, procedures, and results of our AMBON with other MBON projects has been challenging but also rewarding. Among the most obvious overlaps and as a basis for the development of a national MBON were: environmental DNA (including unifying procedures), data management goals, and possible application of satellite metrics to define seascape categories and link to biodiversity measures. The AMBON project has a very strong commitment to data management, and is working closely with its partner AXIOM Data Science on this, and we took a driving role in promoting common data management procedures among the MBON projects. Looking ahead, these elements still feature prominently within the new set of MBON projects that are currently underway. Another shared goal of all MBON projects was to engage in a meaningful way with endusers of the biodiversity information created in the projects. For AMBON, this connection has always been particularly strong with the Bureau of Ocean Energy Management (BOEM), the federal entity managing oil and gas development in the Arctic. While oil extraction activities in the Chukchi Sea were halted during this initial phase of the AMBON project, the mandate of BOEM to support continued ecosystem understanding in a region containing lease sales remains. Coincidentally, BOEM managers also are heavily involved in the leadership of coordinating pan-Arctic biodiversity monitoring efforts through the CBMP (*see Objective 4a*), tightening the multiple links through which AMBON connects as a network with multiple other entities and users.

3. Outreach

The AMBON program implemented a multifaceted approach to outreach activities that included consultations with subsistence harvest co-management groups, informational broadcasts of ongoing field activities via email, participation in regional waterways safety planning meetings, participation scientific workshops and conferences, K-12 classroom visits, and public lectures.

Prior to field activities, the AMBON group would participate in summer and/or fall meetings of the thrice-yearly Alaska Eskimo Whaling Commission (AEWC). These meetings were sometimes scheduled immediately after meetings of the Arctic Waterways Safety Commission (AWSC), where AMBON participation was also included. Presentations to the commissioners would cover study objectives, cruise logistics, timing, funding, and field activities. Follow-up presentations following the field season provided scientific and logistics cruise summaries in an effort to “report back”. As sincere and honest the intentions of these Commission attendances are, we learned that communication and the exchange of “western” science with Indigenous natural observations is a topic that will require a lot more listening and learning from one another. We have encountered so-called “research fatigue” in some of the Commission and community interactions. This is a potential conflict that is increasingly recognized by the overall Arctic research community, scientists, Indigenous peoples, and funding agencies alike, and we understand that it will take all of the partners in these discussions to make progress towards a more harmonious understanding of the Arctic ecosystem.

During the research cruises, daily emails were sent to an email listing of many dozens of people that included coastal village Tribal Coordinators, AEWC commissioners and other coastal community residents. We found that the emails during cruises were a good way to keep the coastal communities informed of current and upcoming cruise activities. Observations from the vessel were well appreciated. The emails also provided a means for the coastal residents to communicate with the research vessel and inform the vessel of subsistence hunting activities or other matters. Examples of daily communications during AMBON research cruises can be found on the AMBON website (https://ambon-us.org/field-work/2015-cruise/).

When embarking or dis-embarking from the research vessel in Nome, AMBON scientists provided public lectures at the UAF Nome campus as part of the "Strait Science" lecture series. These lectures are normally attended by the public and by reporters from the KNOM radio station and the Nome Nugget newspaper, and articles of interest are disseminated across the Bering Strait region.

AMBON PIs also participated in many regional, national and international scientific meetings where program results were presented (see section 5 of this report). Many of these meetings are open to the public (registration required), including locally at the annual Alaska Forum on the Environment (AFE), the Alaska Marine Science Symposium (AMSS) conferences, and the Northern Oil and Gas Forum. AMBON PIs hosted sessions focused on high-latitude ecosystem dynamics at the bi-annual American Geophysical Union (AGU) and Association for the Sciences of Limnology and Oceanography (ALSO) Ocean Science Meeting (OSM). Other scientific and planning meetings with AMBON representation included the Pacific Arctic Group (PAG) annual science and business meetings; meetings of the Circumpolar Biodiversity Monitoring Program and the State of the Arctic Marine Biodiversity Report (SAMBR) via U.S. Arctic Marine Biodiversity meetings; the Arctic Observing Summit (AOS); the Arctic Science Summit Week (ASSW). AMBON results were also highlighted at informational meetings of the Interagency Arctic Research Policy Committee (IARPC) via joint Environmental Intelligence, Marine Ecosystems, and Coastal Resilience Collaboration Team meetings. These meetings saw broad participation by the science community (nationally and internationally) and residents of coastal communities from across the Pacific Arctic (also see details under Objective 4 in section 2 of this report)

The following list presents examples of various outreach activities during the AMBON project:

- AMBON website: http://ambon-us.org/
- AMBON is part of NOAA/IOOS MBON websites http://oceanservice.noaa.gov/news/apr16/mbon.html; https://marinebon.org/
- AMBON highlighted in BOEM Science Notes, April 8, 2016
- AMBON identified as priority biodiversity research in March 2016 US National Strategy for the Arctic Updates
- Website entry at UAF School of Fisheries and Ocean Sciences https://web.sfos.uaf.edu/wordpress/news/?p=1960
- Contact initiated with local community leaders in the Chukchi Sea region (via e-mail and flyers) and presented the project at the Alaska Eskimo Whaling Commission and the Arctic Waterways Safety Committee in December 2016.
- Daily log provided during cruise to >40 individuals in management agencies and local representatives of villages on the North Slope. See http://ambon-us.org/field-work/
- AMBON is an essential partner of the Chukchi Ecosystem Observatory, a mooring array in the northeastern Chukchi Sea that contributes long-term data context to the in-depth AMBON field data and which is retrieved and re-deployed during AMBON cruises. A small introductory video with field footage largely from the AMBON cruise can be found at http://chukchiecosystemobservatory.org/. The AMBON project is credited at the end of the video.
- AMBON presentation as part of the Bering Science Series in Nome, August 2017

- Radio story on AMBON in Nome at KNOM radio, 2017
- News story in Nome Nugget about the AMBON 2017 field effort
- Case study contribution to new edition of *Biodiversity and Climate Change*, edited by Thomas Lovejoy and Lee Hannah, in press, Yale University Press
- Contributions to biodiversity workshop sponsored by Conservation International
- Science Potpourri at University of Alaska Fairbanks – public touch tank experience with Arctic invertebrates
- Local school group visits about the Arctic
- TV life interview (KTUU Anchorage) on Arctic Climate Change
- PIs Cooper and Grebmeier's Arctic webpage at CBL (http://arctic.cbl.umces.edu) provides a platform for highlighting core research activities in the Pacific Arctic, including the AMBON and DBO activities. PIs Grebmeier has given media interviews about the ecosystem changes being observed through multiple US agency research.

4. Data Management

Core data management support and services for AMBON were provided by Axiom Data Science, the technical partner to the Alaska Ocean Observing System (AOOS). The main responsibilities of the Axiom group were assistance with structuring data collected during AMBON cruises in 2015 and 2017, and management of these datasets in the Research Workspace, a web-based platform for sharing, documenting, analyzing, and monitoring data. For these data, metadata records were created using NOAA-compliant ISO 19115 standards in preparation for data archive. Additionally, all final biological datasets were transformed (or are in the process) into the Darwin Core format, following IOOS best practice guidelines for biological standards, for publication through the Ocean Biogeographic Information System (OBIS). All final AMBON datasets have been curated and are publicly available through the MBON data portal (https://l.axds.co/35vYBHw; also see list of datasets below). At this time, the AMBON project has 34 published datasets (some combined into larger topic datasets) on the MBON data portal. Currently there is one dataset in its final state that needs to be archived. There are three provisional datasets, awaiting final data. Additionally, 11 final datasets have been submitted to the Axiom data coordinators, and their metadata are in the process of final review and are either awaiting a signed publication agreement or re-processing to Darwin Core.

The Research Workspace continues to be used as the internal staging area for the storage of AMBON data, sharing information (e.g., presentations, reports) and synthetic products (Figure 13). The Research Workspace is a platform that allows users to manage their science efforts through the entire data management lifecycle in a collaborative, web-based environment. The AMBON Workspace group contains individual PI user and project profiles in which data have been regularly submitted and shared among project collaborators. The volume of AMBON data stored in the Workspace currently amounts to over 1,925 data files, totaling 2.7 GB of data loaded by AMBON researchers. Axiom staff provided technical support to AMBON researchers for loading final, processed datasets to the Workspace, as well as generating descriptive metadata documentation for the final datasets within the integrated Workspace editor. Additionally, Axiom software engineers continued to maintain the Workspace, including resolving bugs and implementing new functionality in response to user feedback.

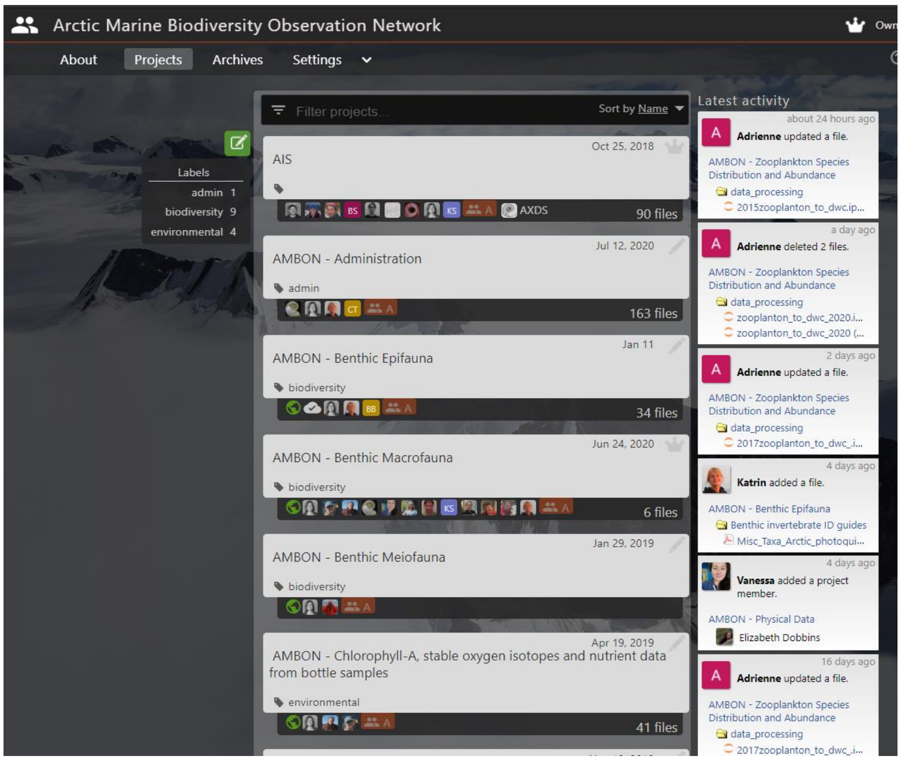


Fig. 13: Screenshot of the AMBON Research Workspace

To maximize data use for analysis, synthesis, review, and application, and to support the MBON biodiversity and ecosystem function goals, data from the AMBON program have been made available through multiple pathways. During the data collection and analysis phases, provisional datasets from individual AMBON projects have been securely available for internal use through the Research Workspace. As datasets were quality-reviewed and finalized including metadata, the data were also made available for exploration and discovery through the public-facing [MBON data portal (https://mbon.ioos.us/)](https://mbon.ioos.us/).

The MBON portal was initiated as a proof-of concept in 2016 (by Axiom Data Science and IOOS) to provide access to a large, diverse set of valuable information for retrospective analysis, synthesis, and model development. During this performance period (in a separate contract with Axiom Data Science and IOOS), one version of the MBON portal infrastructure was released[1] with performance enhancement features to improve the integration of physical, environmental, and biological data. This version release featured: the ability to add custom narratives to station level pages, introduction of service error message and improved issue logging, bug fixes relative to UTC time zone display in the browser, and availability of thematic tags to individual data layers in the data catalog. The portal provides data access, exploration, and analysis for hundreds of relevant datasets for the MBON regions. In addition to mapping and catalog interfaces, the portal offers users custom dashboards (called data views) where users can integrate and compare data to explore relevant data trends. These dashboards can be saved and shared among users to encourage deeper data exploration and collaboration. Through the portal, users are now able to view and download AMBON datasets and metadata in preservation-ready formats (Figure 14). Using the portal functionality, users have the ability to view these datasets by time, spatially parse the data, and/or apply various biodiversity indices calculations to the data as per IOOS MBON guidance (Figure 15).

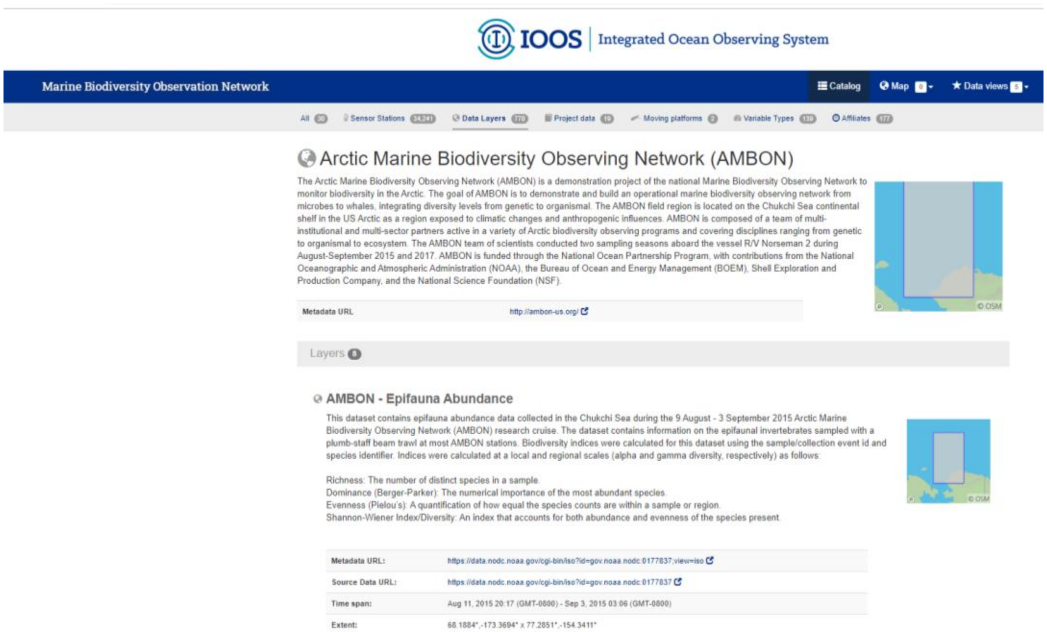


Fig. 14: The MBON Data Portal catalog can be used to search, explore, and access AMBON project datasets: [*https://l.axds.co/2k4JGyC*](https://l.axds.co/2k4JGyC)

[1] Portal release notes: https://axiomdatascience.com/portal-updates/

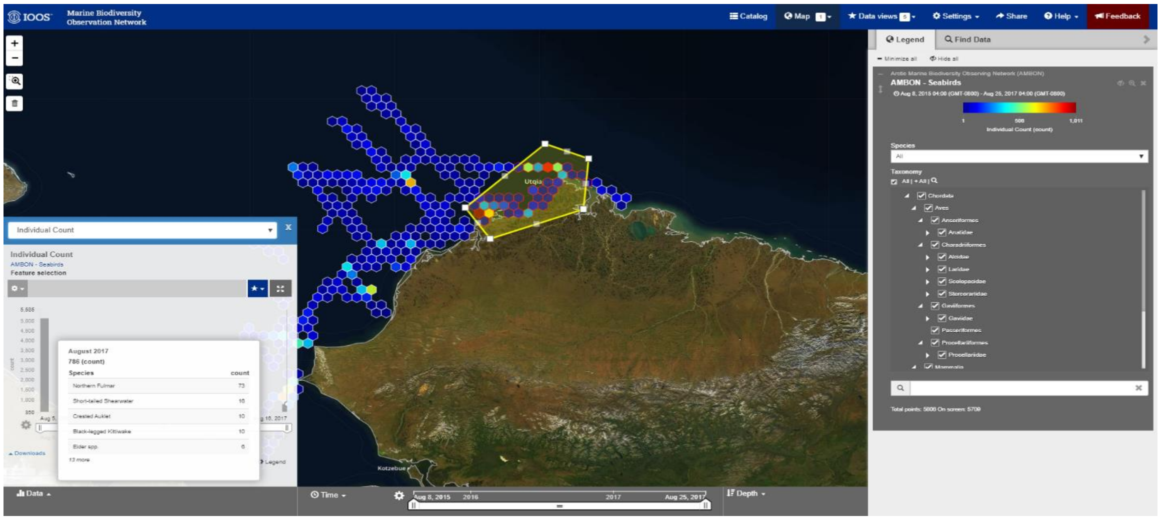


Fig. 15: A screenshot of 2015 and 2017 seabird data available for interactive visualization in the MBON Data Portal: https://l.axds.co/2QKKmus

MBON Data Management Principles

Open Data Sharing

Axiom Data Science and Arctic MBON are committed to open data sharing.

- Datasets from the Arctic MBON program are made publicly available in:
    - the MBON data catalog. Where applicable, these data have been converted for Darwin Core and visualized in the Axiom AMBON data portal.
    - Additionally, these data have been converted to an OBIS-compliant Darwin Core data and metadata format for publishing through OBIS
- Datasets from the AMBON program are archived and made available for download, along with ISO 19115-1 standards-compliant metadata, at NOAA's NCEI data repository

Use of common vocabularies & identifiers, and improved use of metadata conventions

- AMBON data are described in ISO 19115-1 metadata
- AMBON data and metadata format are converted to Darwin Core for visualization
- AMBON data and metadata are converted to an OBIS-compliant Darwin Core variant
- AMBON data are archived, receive an NOAA NCEI accession number, and a digital object identifier (DOI)

Data storage and archiving

- AMBON data are securely stored in Axiom's data center in the Pittock center in Portland, OR
- AMBON data are archived with NOAA NCEI and stored in their data repository

Ongoing participation in interagency discussions related to data management planning and coordination

AMBON has partnered with Axiom Data Science to engage in data management activities with multiple agencies. Axiom Data Science, on behalf of the MBON, participates in interagency discussion and panels for data management including with NOAA NCEI, DataOne Users Group, ESIP's Standardizing Marine Biological Data Cluster, and others.

AMBON dataset status

Dataset	DOI weblink	Processing strategy	DWC link	Archived
Grebmeier, J; Cooper, L (2018). Surface Sediment Size and Chemistry Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise on RV Norseman II from 2015-08-12 to 2015-09-03 and 2017-08-06 to 2017-08-22	https://doi.org/10.25921/zqwr-at45	Python script	ISO 19115-2 (physical data not suitable for DWC)	NCEI Accession 0178029
Kuletz, K; Cushing, D (2018). Marine Bird Sighting Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise on the vessel Norseman II from 2015-08-09 to 2015-09-03.	http://doi.org/10.25921/c796-rz71	SQL & Python script	ISO 19115-2 https://obis.org/dataset/69a06619-6cb4-4c8a-8bb2-41f88c5669a1	NCEI Accession 0177729 https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0177729
Iken, K (2018). Benthic Epifauna Biomass and Abundance Data in the Chukchi Sea, Arctic Marine Biodiversity Observing Network (AMBON) research cruise on the Norseman II from 2015-08-09 to 2015-09-03.	https://doi.org/10.25921/b2g4-bs86	Python Script	In progress	NCEI Accession 0177837
Kuletz, K; Cushing, D (2018). Marine Bird Sighting Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise on the vessel Norseman II, 05- 25 August 2017.	https://doi.org/10.25921/s7a1-bp57	SQL & Python script	ISO 19115-2 https://obis.org/dataset/7eee0f1c-5afc-4135-94df-f3ecb169fa38	NCEI Accession 0178638 https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0178638
Stafford, K (2018). Vessel line-transect surveys of Arctic marine mammals in the Chukchi Sea, Arctic Marine Biodiversity Observing Network (AMBON) research cruise on the vessel Norseman II, 2015-08-09 - 2015-09-03.	https://doi.org/10.25921/ddbd-wk50	SQL & Python script	ISO 19115-2 https://obis.org/dataset/f42a54d2-4283-47c9-a65b-49b34a34e3c2 https://obis.org/dataset/6e930622-4421-41f8-b18b-f8d11dd51e15	NCEI Accession 0177802

Stafford, K (2018). Vessel line-transect surveys of Arctic marine mammals in the Chukchi Sea, Arctic Marine Biodiversity Observing Network (AMBON) research cruise on the vessel Norseman II from 2017-08-05 to - 2017-08-25	https://doi.org/10.25921/3kbx-vn96	SQL & Python script	ISO 19115-2 https://obis.org/dataset/a2e29f6c-4978-438f-8cc4-f6ea98b34141	NCEI Accession 0177817
Mueter, F (2019). Fish length, weight, and abundance data from trawl surveys in the Chukchi Sea, Arctic Marine Biodiversity Observing Network (AMBON) research cruise on the vessel Norseman II from 2015-08-11 to 2015-09-03.	https://doi.org/10.25921/qdhp-qg47	Python Script	https://www1.usgs.gov/obis-usa/ipt/resource?r=ambon_fish_hauls_2015	NCEI Accession 0208100 https://accession.nodc.noaa.gov/0208100
Mueter, F (2019). Fish Haul and Specimen Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2015	https://doi.org/10.25921/qdhp-qg47	Python Script	https://www1.usgs.gov/obis-usa/ipt/resource?r=ambon_fish_hauls_2015	https://mbon.ioos.us/#metadata/8f262403-8de6-4128-9857-9798d062c2b5/project/folder_metadata/1814107
Iken, K (2020). Benthic epifauna biomass and abundance data, Arctic Marine Biodiversity Observing Network (AMBON) research cruise, August 2017	https://doi.org/10.25921/py0j-mz96	Python Script	https://www1.usgs.gov/obis-usa/ipt/resource?r=ambon_epifauna_2017	NCEI Accession 0213519
Collins, R.E.; 2019. Metabarcoding surveys of the Arctic marine environment.	no	n/a	none	Under overall NCBI Accession: PRJNA421293 https://www.ncbi.nlm.nih.gov/bioproject/421293,
Danielson, S.; CTD Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2015	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#metadata/d3b1bec1-600a-4643-a610-ff83ac6853d0/project
Danielson, S.; CTD Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2017	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#metadata/d3b1bec1-600a-4643-a610-ff83ac6853d0/project

Danielson, S.; ADCP Data Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2015	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#metadata/d3b1bec1-600a-4643-a610-ff83ac6853d0/project/folder_metadata/2533059
Danielson, S.; Weather Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2015	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#metadata/d3b1bec1-600a-4643-a610-ff83ac6853d0/project
Cooper, L, Grebmeier, J.; Chlorophyll-A, stable oxygen isotopes and nutrient data from bottle samples, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2015	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#metadata/dac64be5-67c5-44a8-aed0-c79353f436e3/project
Cooper, L, Grebmeier, J.; Chlorophyll-A, stable oxygen isotopes and nutrient data from bottle samples, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2017	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	Pending https://mbon.ioos.us/#platform/239966c2-85ea-5826-b801-51740a50b176/v2
Mueter, F.; Fish Haul and Specimen Data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2017	Pending	Python Script	ISO 19115-2	pending
Hopcroft, R.R.; Zooplankton Species Distribution and Abundance Data, with 150 µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2015	Pending	Python Script	ISO 19115-2	pending
Hopcroft, R.R.; Zooplankton Species Distribution and Abundance Data, with 505 µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August - September 2015	Pending	Python Script	ISO 19115-2	pending

Hopcroft, R.R.; Zooplankton Species Distribution and Abundance Data, with 150µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2017	Pending	Python Script	ISO 19115-2	pending
Hopcroft, R.R.; Zooplankton Species Distribution and Abundance Data, with 505 µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2017	Pending	Python Script	ISO 19115-2	pending
Iken, K. Stable carbon and nitrogen isotope data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2015	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	pending
Iken, K. Stable carbon and nitrogen isotope data, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, August 2017	Pending	Python Script	ISO 19115-2, (physical data not suitable for DWC)	pending

5. Presentations

Presenter is underlined

Iken K. AMBON – The Arctic Marine Biodiversity Observing Network. "All BON meeting" College Park, Maryland, 24 April 2015 (oral presentation)

Iken K, Bluhm BA, Collins RE, Cooper LW, Danielson S, Grebmeier JM, Hopcroft R, Kuletz K, Mueter F, Moore SE, Stafford K, Bochenek R. AMBON – a US Arctic Marine Biodiversity Observing Network. Arctic Observing Open Science meeting, 17-19 November 2015, Seattle (poster presentation)

Iken K, Danielson S, Cooper LW, Grebmeier JM, Hopcroft R, Kuletz K, Stafford K, Mueter F, Collins RE, Bluhm BA, Moore SE, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. X-MBON meeting, Monterey Bay, 14-15 October 2015 (oral presentation)

Iken K, Bluhm BA, Kuletz K, Collins E, Cooper LW, Danielson S, Grebmeier JM, Hopcroft R, Mueter F, Moore SE, Stafford K, Bochenek R. Arctic Marine Biodiversity Monitoring Network: Towards integrating seabird monitoring with a multi-disciplinary program for the Arctic. World Seabird Union meeting, Cape Town, South Africa, 26-30 October 2015 (poster presentation)

Iken K, Danielson S, Cooper L, Grebmeier J, Hopcroft R, Kuletz K, Stafford K, Mueter F, Collins RE, Bluhm BA, Moore S, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. Alaska Marine Science Symposium, Anchorage AK, 25-28 Jan 2016 (oral presentation)

Divine LM, Mueter FJ, Kruse GH, Bluhm BA, Iken K. New estimates of growth, size-at-maturity, mortality and biomass of snow crab. *Chionoecetes opilio*, in the Arctic Ocean off Alaska. Alaska Marine Science Symposium, Anchorage AK, 25-28 Jan 2016 (poster presentation).

Zinkann AC, Iken K. Contribution of microbially-derived carbon sources to Chukchi Sea benthic food webs. Alaska Marine Science Symposium, Anchorage AK, 25-28 Jan 2016 (poster presentation).

Mueller-Karger FE, Iken K, Miller RJ, Duffy JE, Chavez F, Montes E. A demonstration Marine Biodiversity Observing Network (MBON): Understanding marine life and its role in maintaining ecosystem services. Ocean Sciences Meeting, New Orleans LA, 21-26 Feb 2016 (poster presentation)

Iken K, Danielson S, Cooper L, Grebmeier J, Hopcroft R, Kuletz K, Stafford K, Mueter F, Collins RE, Bluhm BA, Moore S, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. Ocean Sciences Meeting, New Orleans LA, 21-26 Feb 2016 (poster presentation)

Cooper LW, Grebmeier JM, Danielson S, Hopcroft R, Iken K, Kuletz K, Stafford K, Mueter F, Collins RE, Bluhm BA, Moore SE, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. Marine Biodiversity Observing Network (MBON) All Hands meeting, Silver Spring, MD, 3 May 2016 (oral presentation)

Kuletz, K., E. Osnas, E. Labunski, D. Cushing. The Distributed Biological Observatory: A means of measuring change in the Arctic seabird community. Pacific Seabird Group, Tacoma, WA, February 2017. (Poster presentation)

Labunski, L., K. Kuletz. Long-term Seabird Data for a Changing Arctic. Pacific Seabird Group Annual Meeting, Tacoma, WA, February 2017. (Oral Presentation).

Kuletz, K. Seabirds of the Pacific Arctic & circumpolar regions. ICES/PAME Central Arctic Working Group, 19-21 April, 2017, Seattle WA. (Oral Presentation)

Smoot CA, Hopcroft RR. Zooplankton communities of the Chukchi Sea during August 2015: results from the Arctic Marine Biodiversity Observing Network. Alaska Marine Science Symposium. Anchorage AK 23-27 January 2017. (poster presentation)

Iken K, Grebmeier J, Cooper L, Danielson S. Small and large-scale variability in Chukchi Sea epibenthos – recommendation for monitoring design. Alaska Marine Science Symposium. Anchorage AK 23-27 January 2017. (poster presentation)

Smoot CA, Hopcroft RR. Gateway to the Arctic: Summer zooplankton communities of the Chukchi Sea 2008- 2015. Aquatic Sciences Meeting, Honolulu HI 26 February-3 March 2017. (poster presentation)

Kuletz K, Cushing D, Osnas E, Labunski E, Gall A, Morgan T. Seabirds as Indicators for the Distributed Biological Observatory and Other Long-term Marine Monitoring Programs. Alaska Marine Science Symposium, January 2018, Anchorage AK (oral presentation)

Mendoza-Islas H, Hopcroft RR. Hydromedusae and ctenophores of the northeastern Chukchi Sea during 2017. Alaska Marine Science Symposium, January 2018, Anchorage AK (poster presentation)

Iken K, Mueter F, Danielson S, Cooper LW, Grebmeier JM, Bluhm BA. Epibenthos and Demersal Fish Community Structure in the Chukchi Sea in Relation to Environmental Variables. Arctic Frontiers, January 2018, Tromso Norway (poster presentation)

Kuletz K, Cushing D, Osnas E, Labunski E, Gall A, Morgan T. What the Distributed Biological Observatory Can Tell Us About Seabirds, and Vice Versa. Ocean Sciences Meeting, February 2018, Portland OR (oral presentation)

Mendoza-Islas H, Hopcroft RR. Hydromedusae and ctenophores of the northeastern Chukchi Sea during 2017. Ocean Sciences Meeting, February 2018, Portland OR (poster presentation)

Iken K, Mueter F, Danielson S, Cooper LW, Grebmeier JM, Bluhm BA. Epibenthos and Demersal Fish Community Structure in the Chukchi Sea in Relation to Environmental Variables. Ocean Sciences Meeting, February 2018, Portland OR (poster presentation)

Hopcroft RR, Questel JM, Smoot CA, Clarke-Hopcroft C. Inter-annual Variability of the Zooplankton Communities in the Northeastern Chukchi Sea: a Decadal Perspective. Ocean Sciences Meeting, February 2018, Portland OR (poster presentation)

Kuletz K, et al. Seabird Communities of the Pacific Arctic and the Distributed Biological Observatory- A Broad Scale Monitoring Array. Pacific Seabird Group Meeting, February 2018, La Paz, Mexico (oral presentation)

Cooper L, Iken K, Grebmeier J, Danielson S, Mueter F, Hopcroft R, Stafford K, Kuletz K, Collins E, Kavanaugh M, Bluhm B, Moore S, Buckelew S, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. NASA Ecological Forecasting meeting, April 2018, Washington DC (oral presentation)

Iken K, Cooper L, Grebmeier J, Danielson S, Mueter F, Hopcroft R, Stafford K, Kuletz K, Collins E, Kavanaugh M, Bluhm B, Moore S, Buckelew S, Bochenek R. AMBON – Arctic Marine Biodiversity Observing Network. MBON all-hands meeting, April 2018, Washington DC (oral presentation)

Mueter FJ, Drinkwater K, Saitoh, SI. Resilience and adaptive capacity of Arctic marine systems under a changing climate. Mid-Term Meeting of the Belmont Forum Arctic Observing and Science for Sustainability Collaborative Research Action (CRA), 8-10 December 2018, Washington D.C. (oral presentation)

Sutton L, Iken K, Bluhm B, Mueter F. 2019. A comparison in functional diversity of two Alaskan shelf systems. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January 2019 (oral presentation)

Zinkann AC, Iken K, O'Brien D, Wooller M. 2019 Digging deep: Depth distribution and utilization of carbon sources in Chukchi Sea sediments. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January 2019 (oral presentation)

Grebmeier J, Cooper L, Goethel C, Kedra M, Iken K. 2019. Pelagic-benthic coupling in the Chukchi Sea ecosystem: a key part of the Arctic Marine Biodiversity Observing Network (AMBON). Alaska Marine Science Symposium, Anchorage, AK. 28-31 January 2019 (oral presentation)

Chapman Z, Mueter F, Norcross BL, Oxman D. 2019. Identifying hatch dates and potential hatch location through otolith analysis for Arctic Cod (*Boreogadus saida*). Alaska Marine Science Symposium Anchorage, AK. 28-31 January 2019 (poster presentation)

Lekanoff RM, Collins RE, McDonnell AMP. 2019. Characterizing gene functions of microbes and their role in the carbon cycle of the Bering and Chukchi seas. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January 2019 (poster presentation)

Wooller M, Kungcheol C, Rowe A, Blanchard A, Iken K, O'Brien D. 2019. Identifying sources of essentia l amino acids to benthic organisms in the Beaufort and Chukchi Sea using stable isotope fingerprinting. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January 2019 (poster presentation)

Sutton L, Iken K, Bluhm B, Mueter F. 2019. A comparison in functional diversity of two Alaskan shelf systems. CMI Annual Review, Anchorage, AK. 1 February 2019 (oral presentation)

Chapman Z, Mueter FJ. Identifying hatch dates and potential hatch location through otolith analysis fo r Arctic cod (*Boreogadus saida*). CMI Annual Review, Anchorage, AK. 1 February 2019 (oral presentation)

Wooller M, Kungcheol C, Rowe A, Blanchard A, Iken K, O'Brien D. 2019. Identifying sources of essential amino acids to benthic organisms in the Beaufort and Chukchi Sea using stable isotope fingerprinting. CMI Annual Review, Anchorage, AK. 1 February 2019 (oral presentation)

Zinkann AC, Iken K, O'Brien D, Wooller M. 2019 Digging deep: Depth distribution and utilization of carbon sources in Chukchi Sea sediments. Benthic Ecology Meeting, St. John, Canada. 3-6 April 2019 (oral presentation)

Lekanoff RM, McDonnell AMP, Collins RE. 2019. Phytoplankton microdiversity in the Bering and Chukc hi Seas. Gordon Research Conference on Polar Marine Science, Lucca, Italy. (poster presentation)

Kuletz K, Cushing D, Osnas E, Labunski E, Gall A. 2019. Pacific Arctic seabird communities: a decade of change viewed through the lens of the Distributed Biological Observatory's at-sea surveys. American Ornithological Society, 24-28 June 2019, Anchorage, Alaska (oral presentation)

Kuletz K, Cushing D, Osnas E, Mueter F, Labunski E, Gall A. 2019. Pacific Arctic seabird communities in a time of change. PICES workshop, Oct 16, and participated in part of PICES annual meeting, Oct 17-22, 2019, Victoria, British Columbia. (oral presentation)

Grebmeier JM, et al. 2019. Plenary speaker, 25th KOPRI International Polar Symposium, Incheon, South Korea, May 2019

Grebmeier JM, et al. 2019. Plenary Speaker, Arctic Science Summit Week, Archangelsk, Russia, May 2019

Mueter, F.J., Marsh J., Vestfals C., Levine R., de Robertis A., GO-WEST team. Fisheries studies, with a focus on Arctic cod (*Boreogadus saida*), in the Pacific Arctic. IARPC (Interagency Arctic Research Policy Committee) Marine Ecosystems collaboration team webinar. March 25, 2020. (oral presentation)

Kuletz, K., Cushing D., Mueter F., Osnas E., Kimmel D., Labunski E., Gall A., Renner H., Dragoo D. Seabirds signal changes in the Pacific Arctic. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020 (oral presentation)

Kuletz, K., Cushing D., Mueter F., Osnas E., Kimmel D., Labunski E., Gall A., Renner H., Dragoo D. Seabirds signal changes in the Pacific Arctic. Pacific Seabird Group Meeting in Portland, Oregon, February 2020
(oral presentation)

Kuletz, K., Cushing D., Mueter F., Osnas E., Kimmel D., Labunski E., Gall A., Renner H., Dragoo D. Seabirds signal changes in the Pacific Arctic. Ocean Sciences Meeting in San Diego, California, February 2020 (oral presentation)

Lanctot, R., Krietsch J., Valcu M., Kuletz K., Saalfeld S., Cushing D., Robards M., McGuire R., Schulte S., Brown S., Latty C., Harrison A., Kempenaers B. Use of satellite tagged birds and at-sea surveys to document Red Phalarope distribution and migration routes in the Beaufort, Chukchi and Bering Seas. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. (oral presentation)

Raymond, R., Kuletz K., Lanctot R., Labunski E. BOEM's Alaska Environmental Studies Program: A Review of the At-Sea Seabird Surveys and Red Phalarope Tracking Study. Ocean Science Meeting, San Diego, California, February 2020. (poster presentation)

Farley, E., Danielson S., Huntington H., Ladd C., Stafford K., et al. (incl. Mueter, F.J., Kuletz, K.J., Hopcroft, R.R.). Arctic Integrated Ecosystem Research Program: Are we experiencing the future Arctic? Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. (oral presentation)

Questel, J.M., Smoot C.A., Clarke C., Hopcroft R.R. Decadal variability in mesozooplankton communities of the Northeastern Chukchi Sea: 2008 – 2017. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. (poster presentation)

Sutton, L., Iken K., Mueter F., Bluhm B.A. The influence of environmental drivers on functional diversity across Alaskan Arctic epibenthic shelf communities. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. (poster presentation)

Grebmeier, J.M., Cooper L.W., Frey K.E., Moore S.E. Biological time series observations in the Pacific Arctic: a key to understanding ecosystem change. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. (poster presentation)

Wegner C., Brown T.A., Lalande C., Grebmeier J.M., Cooper L.W. Utilization and Importance of Sea Ice Derived Organic Carbon to Benthic Communities of the Chukchi Sea: Evidence from Highly Branched Isoprenoid Biomarkers. Ocean Science Meeting, San Diego, California, February 2020 (oral presentation)

Goethel C., Grebmeier J.M., Cooper L.W., Rowe C. Sediment oxygen consumption in the Pacific Arctic: Impacts of increased temperature and food supply on the benthic community and individual dominant organisms. Ocean Science Meeting, San Diego, California, February 2020 (oral presentation)

Danielson S.L. Heat over the Pacific Arctic Continental Shelves: Recent Changes in Content, Surface Fluxes and Throughput. Ocean Science Meeting, San Diego, California, February 2020. (poster presentation)

Grebmeier J.M., Moore S., Cooper L.W. Recent Changes in Benthic Prey Populations in Relation to Gray Whale Feeding in the Pacific Arctic. Ocean Science Meeting, San Diego, California, February 2020. (poster presentation)

6. Publications

*AMBON PI authors in **bold***

CAFF. 2017. State of the Arctic Marine Biodiversity: Key Findings and Advice for Monitoring. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. ISBN: 978-9935-431- 62-2. https://www.arcticbiodiversity.is/marine (contributing AMBON authors: **R.E. Collins, R. Hopcroft, K. Kuletz, K. Iken**)

Danielson, S.L., Iken, K., Hauri, C., **Hopcroft, R.R.,** McDonnell, A.M., Winsor, P., Lalande, C., **Grebmeier, J.M., Cooper, L.W.,** Horne, J.K. **Stafford, K.M.,** 2017. Collaborative approaches to multi-disciplinary monitoring of the Chukchi shelf marine ecosystem: Networks of networks for maintaining long-term Arctic observations. In *OCEANS 2017-Anchorage* (pp. 1-7). IEEE.

Muller-Karger FE, Miloslavich P, Bax NJ, Simmons S, Costello MJ, Sousa Pinto I, Canonico G, Turner W, Gill M, Montes E, Best B, Pearlman J, Halpin P, Dunn D, Benson A, Martin C, Weatherdon L, Appeltans W, Provoost P, Klein E, Kelble C, Miller RJ, Chavez F, **Iken K**, Chiba S, Obura D, Navarro LM, Pereira HM, Allain V, Batten S, Benedetti-Cecchi L, Duffy JE, Kudela RM, Rebelo L-M, Shin Y, Geller G. 2018 Advancing Marine Biological Observations and Data Requirements of the Complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) Frameworks. 2018. *Frontiers in Marine Science* Vol 5, Art. 211, https://doi.org/10.3389/fmars.2018.00211

Walsh JE, Thomen RL, Bhatt US, Bieniek PA, Brettschneider B, Brubaker M, Danielson S, Lader R, Fetterer F, Holderied K, **Iken K**, Mahoney A, McCammon M0, Partain J. 2018. The high latitude marine heat wave of 2016 and its impacts on Alaska. *Bulletin of the American Meterological Society* 99: S39-S43. https://doi.org/10.1175/BAMS-D-17-0105.1

Divine LM, **Mueter FJ,** Kruse GH, **Bluhm BA,** Jewett SC, **Iken K.** 2019. New estimates of weight-at-size, maturity-at-size, fecundity, mortality and biomass of snow crab, *Chionoecetes opilio*, in the Arctic Ocean off Alaska. *Fisheries Research* 218: 246-258

Kuletz K, Cushing DA, Osnas EE, Labunski EA, Gall AE. 2019. Representation of the Pacific Arctic seabird community within the Distributed Biological Observatory array, 2007-2015. *Deep Sea Research II* 162:191-210. https://doi.org/10.1016/j.dsr2.2019.04.001

Grebmeier JM, Moore SE, Cooper LW, Frey KE. 2019. The Distributed Biological Observatory: A change detection array in the Pacific Arctic - An Introduction. *Deep-Sea Research Part II* 162: 1–7. https://doi.org/10.1016/j.dsr2.2019.05.005

Waga H, Hirawake T, Fujiwara A, **Grebmeier JM**, Saitoh S-I. 2019. Impact of spatiotemporal variability in phytoplankton size structure on benthic macrofaunal distribution in the Pacific Arctic. *Deep-sea Research II Topical Studies in Oceanography* 162: 114-126. https://doi.org/10.1016/j.dsr2.2018.10.008.

Iken K, Mueter FJ, Grebmeier J, Cooper L, Danielson SL, Bluhm B. 2019. Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea. *Deep-Sea Research II* 162: 180-190. https://doi.org/10.1016/j.dsr2.2018.11.005

Canonico G, Buttigieg PL, Montes E, Stepien CA, Wright D, Benson A, Helmuth B, Costello MJ, Muller-Karger FE, Sousa Pinto I, Saeedi H, Newton JA, Appeltans W, Bednaršek N, Bodrossy L, Best BD, Brandt A, Goodwin K, **Iken K,** Marques A, Miloslavich P, Ostrowski M, Turner W, Achterberg EP, Barry T, Defeo O, Bigatti G, Henry L-A, Ramiro Sanchez B, Durán Muñoz P, Mar Sacau Cuadrado M, Morato T, Roberts M, Garralda Garcia-Alegre A, Murton BJ. 2019. Global observational needs and resources for marine biodiversity. *Frontiers in Marine Science* https://doi.org/10.3389/fmars.2019.00367

Rowe AG, **Iken K**, Blanchard A, O'Brien DM, Døving Osvik R, Uradnikova M, Dunton K, Wooller MJ. 2019. Estimates of primary production sources to Arctic bivalves using amino acid stable carbon isotope fingerprinting. *Isotopes in Environmental and Health Studies,* https://doi.org/10.1080/10256016.2019.1620742

Ershova EA, Descoteaux R, Wangensteen OS, **Iken K**, **Hopcroft RR,** Smoot C, **Grebmeier JM, Bluhm BA. 2019**. Diversity and distribution of meroplanktonic larvae in the Pacific Arctic and connectivity with adult benthic invertebrate communities. *Frontiers in Marine Science* https://doi.org/10.3389/fmars.2019.00490

Lee, C.M., Starkweather S., Eicken H., Timmermans M-L., Wilkinson J., Sandven S., Dukhovskoy D., Gerland S., **Grebmeier J.M.**, Intrieri J., Kang S.-H., McCammon M., Polyakov I., Rabe B., Seeyave S., Volkov D., Beszczynska-Möller A., Dzieciuch M., Goni G.J., King A., Olsen A., Rossby T., Sagen H., Skagseth Ø., Søiland H., Sørensen K. 2019. A framework for the development, design and implementation of a Sustained Arctic Ocean Observing System. *Frontiers in Marine Science 6*, Article 451; doi: 10.3389/fmars.2019.00451.

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

Danielson, S.L., Ahkinga O., Ashjian C., Basyuk E., **Cooper L.W.,** Eisner L., Farley E., **Iken K.B., Grebmeier J.M.**, Juranek L., Khen G., Jayne S., Kikuchi T., Ladd C., Lu K., McCabe R.M., Moore G.W.K., Nishino S., Ozenna F., Pickart R.S., Polyakov I., Stabeno P.J., Thoman R., Wood K., Williams W.J., Woodgate R.A., Weingartner T.J. 2020. Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves. *Deep-Sea Research II Topical Studies in Oceanography* p. 104781, https://doi.org/10.1016/j.dsr2.2020.104781

Koch, C.W., **Cooper, L.W.,** Lalande, C., Brown, T.A., Frey, K.E., **Grebmeier, J.M.** 2020. Seasonal and latitudinal variations in sea ice algae deposition in the Northern Bering and Chukchi Seas determined by algal biomarkers. *PLoS ONE* 15(4): e0231178. https://doi.org/10.1371/journal.pone.0231178

Lalande, C., **Grebmeier, J.M**., **Hopcroft, R.R., Danielson, S.L.** 2020. Annual cycle of export fluxes of biogenic matter near Hanna Shoal in the northeast Chukchi Sea. *Deep-sea Research II Topical Studies in Oceanography*, doi.org/10.1016/j.dsr2.2020.104730.

Waga, H., Hirawke T., **Grebmeier J.M.** 2020. Recent change in benthic macrofaunal community composition in relation to physical forcing in the Pacific Arctic. *Polar Biology* 43, 285–294, https://doi.org/10.1007/s00300-020-02632-3

Forster, C.E., Norcross, B.L., **Mueter, F.J.,** Logerwell, E.A., Seitz, A.C. 2020. Spatial patterns, environmental correlates, and potential seasonal migration triangle of polar cod (*Boreogadus saida*) distribution in the Chukchi and Beaufort seas. Polar Biology, 43: 1073–1094.

Sutton, L., **Iken, K.**, **Bluhm, B.A., Mueter, F.J**. 2020. Comparison of functional diversity of two Alaskan Arctic shelf epibenthic communities. Mar*ine Ecology Progress Series* 651: 1-21

Thorson, J. T., Fossheim, M., Mueter, F. J., Olsen, E., Lauth, R. R., Primicerio, R., Husson, B., et al. 2019. Comparison of near-bottom fish densities show rapid community and population shifts in Bering and Barents seas. Department of Commerce, NOAA, http://www.arctic.noaa.gov/Report-Card.

Kuletz, K., Cushing, D., Labunski E. 2020. Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming, 2017-2019. A special Bering Sea issue in *Deep Sea Research II* 181-182: 104913

Danielson, S.L., Hennon T.D., Hedstrom K.S., Pnyushkov A., Polyakov I.V., Carmack E., Filchuk K., Janout M.A., Makhotin M., Williams W.J., Padman L.,2020. Oceanic routing of wind-sourced energy along the Arctic continental shelves, *Frontiers in Marine Science - Global Change and the Future Ocean*, DOI: 10.3389/fmars.2020.00509

Romano, M, Renner HM, **Kuletz KJ,** Parrish JK, Jones T, Burgess HK, Cushing DA, Causey D. *Accepted pending revision*. Die-offs and reproductive failure of murres in the Bering and Chukchi Seas in 2018. *Deep Sea Research II, Special Issue* vol 181-182, https://doi.org/10.1016/j.dsr2.2020.104877

Deary, A.L, Vestfals, C.D, Logerwell, E.A, Goldstein, E.D., Stabeno, P.J., Danielson, S.L., **Mueter, F.J.,** Duffy-Anderson, J.T. Seasonal abundance, distribution, and growth of the early life stages of Polar Cod (*Boreogadus saida*) and Saffron Cod (*Eleginus gracilis*) in the US Arctic during a warm year. In revision at *Polar Biology*.

Zinkann, A-C., Wooller M.J., Leigh M.B., **Danielson, S.L.,** Gibson, G., **Iken, K.** Depth distribution of organic carbon sources in Arctic Chukchi Sea sediments. in review at *Deep-Sea Research II*.

Zinkann, A-C., Wooller, M.J., O'Brien, D., **Iken, K.** Does feeding type matter? Contribution of organic matter sources to benthic invertebrates on the Arctic Chukchi Sea shelf. In review at *Food Webs*

Zinkann, A-C., Gibson, G., **Danielson, S., Iken, K.** The Arctic Chukchi Sea food web: simulating ecosystem impacts of future changes in organic matter flow. In review at Ecological Modeling.

7. Significant collaboration meetings

- **Annual AMBON PI meetings**
- **Participation in regular xMBON conference calls**
- **Participation in annual MBON All Hands meetings**
- International (pan-Arctic) networking occurred during the CBMP (Circumpolar Biodiversity Monitoring Program) meeting in Iceland on 14-17 April. Iken participated virtually and Bluhm participated in person.
- Several AMBON PIs participated in Arctic Summit Week, Toyama Japan, on 23-30 April 2015.
- Provided slide on AMBON for MBON presentation at the GEO-XII Plenary & Mexico City Ministerial Summit, 11-12 November 2015, Mexico City.
- AMBON is included in the 10-year Implementation Plan (IP) for the Distributed Biological Observatory (DBO), as developed by the DBO Collaboration Team of the Interagency Arctic Research Policy Committee (IARPC); a pdf of the DBO IP is available here: http://www.iarpccollaborations.org/teams/Distributed-Biological-Observatory
- Introduction about AMBON to the International Arctic Research Program Collaboration (IARPC) group – Chukchi & Beaufort Seas group, archived on the IARPC website as webinar (member access necessary, http://www.iarpccollaborations.org/members/documents/4475)
- ICES/PAME Central Arctic Working Group, 19-21 April, 2017, Seattle WA
- Pacific Seabird Group Annual Meeting, Tacoma, WA, February 2017
- Participation in the 2017 Pacific Arctic Group (PAG) Fall Meeting (6-7 Nov 2017, Seattle, WA), update to PAG members about AMBON cruise and activities

- Participation in the 2017 DBO Workshop (8-9 Nov 2017, Seattle WA)
- Participation in annual CBMP meeting (Circumpolar Biodiversity Monitoring Program)
- Participation as one of the supporting projects of the NPRB Arctic Integrated Ecosystem Research Project PI meeting (6-8 March 2018, Anchorage AK), discuss collaborative data sets and research efforts
- Participation in the Circumpolar Seabird Group (an Expert Network of CAFF/Arctic Council) at their annual meeting (13-16 March 2018, Cambridge, UK), included presentation of AMBON data that add to a 40+yr time series for marine bird distribution in Arctic offshore waters
- Participation in the National Coastal Ecosystem Mooring Workshop (20-21 March 2018, Seattle WA), discuss mooring efforts
- Continued participation in meetings of ICES/PICES/PAME that produced updated distribution maps (incl. AMBON data) in the seabird section of the "Integrated Ecosystem Assessment for the Central Arctic Ocean"
- Participation as one of the supporting projects of the NPRB Arctic Integrated Ecosystem Research Project PI meeting (6-8 March 2018, Anchorage AK), discuss collaborative data sets and research efforts
- Participation in Ocean Sciences meeting, Portland POR, February 2018 – Iken, Danielson and Hopcroft co-led a special session regarding Arctic ecosystems
- Participation in the Circumpolar Seabird Group (an Expert Network of CAFF/Arctic Council) at their annual meeting (13-16 March 2018, Cambridge, UK), included presentation of AMBON data that add to a 40+yr time series for marine bird distribution in Arctic offshore waters
- Mid-term Meeting of the Belmont Forum Arctic Observing and Science for Sustainability Collaborative Research Action (CRA), 8-10 December 2018, Washington D.C.
- Gordon Research Conference on Polar Marine Science, Lucca, Italy
- Gave a presentation on the State of the Arctic Marine Biodiversity Report, which included AMBON seabird data, for the U.S. Arctic Marine Biodiversity Monitoring meeting, May 6-7 in Anchorage. This is a working group of the Conservation of Arctic Flora and Fauna-Circumpolar Biodiversity Monitoring Program (CAFF-CBMP).
- Participated in Interagency Arctic Research Policy Committee. Presented updates via webinar, 28 August 2019.
- Completed revisions of seabird section for the ICES/PICES/PAME/ Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean (WGICA) seabird section. AMBON data was integrated in the maps and figures; September 2019.
- Grebmeier JM, et al. 2019. Invited seminar: Old Dominion University, Norfolk, VA, September 2019
- Grebmeier JM, et al. 2019. Promotion seminar: Horn Point Laboratory/UMCES, October 2019
- Grebmeier JM, et al. 2019. Invited seminar: East China Normal University, Shanghai, China, October 2019
- CBMP Annual Meeting, held 5-7 November 2019 in Nuuk, Greenland,
- The IARPC Arctic Research Plan for 2017-2021 includes Performance Elements that are specific to the biodiversity sampling completed under AMBON and we provide updates to this performance element (AMBON lead PI Iken is the lead of Performance Element 4.1.2 on marine biodiversity
- 5th DBO data workshop in Seattle, WA in January 22-23, 2020

- Presented update on seabird studies for Distributed Biological Observatory Workshop. Seattle, WA, 22-23 January 2020.
- Collected macrofauna data for a pan-arctic synthesis within the framework of the CBMP
- Presented preliminary, integrated results from projects (including AMBON) at the Arctic Integrated Ecosystem Research Project-Principal Instigator's meeting in Anchorage, Alaska, February 2020.
- Presented results based on our surveys to several working groups at the Pacific Seabird Group (PSG) annual meeting, including the Kittlitz's Murrelet Technical Committee and the Tufted Puffin Technical Committee. Portland, Oregon, February 2020.
- Provide periodic updates to IARPC (Interagency Arctic Research Policy Committee)
- Grebmeier is co-chair for the US Interagency Arctic Research Policy (IARPC) Ecosystem Collaborative Team
- DBO data workshop in Seattle, WA in January 22-23, 2020, with cross-over synergies to AMBON
- Participation in monthly CBMP leadership zoom meetings, summer 2020
- National Academies BOEM Standing Committee meeting, New Orleans, LA,
- Invited panelist, National Geospatial Agency, Arctic Domain Awareness, Springfield, VA
- US Naval Academy, Annapolis, MD,
- Invited participant, The New Arctic Ocean and changing paradigms, Weimar, Germany
- Invited seminar, NASA Goddard Space Center, Greenbelt, MD
- Invited committee member, NASA Icy Worlds, Mt. View, California
- NASA Network for Ocean Worlds first committee meeting
- International Science Advisory Board, Ocean Networks Canada
- Promotion seminar: Appalachian Laboratory/UMCES, January 2020
- Virtual 6th International Symposium on Arctic Research, Tokyo, Japan (COVID-19 in person meeting cancelled)
- Virtual Arctic Science Summit Week 2020, Akuyeri, Iceland (COVID-19 in person meeting cancelled)
- Cooper was the Chair of the Marine Working Group of the International Arctic Science Committee until the end of March 2020 where discussions of biodiversity in the Arctic, including AMBON and DBO results, have been presented.
- Session leads during the Ocean Sciences meeting, San Diego: Ecosystem Structure and Processes in a Changing Arctic (HE41A) 16-21 Feb 2020 (Danielson, Cooper, Grebmeier, Iken)
- Town Hall organizer at Ocean Sciences meeting, San Diego: Scientific Response to an Ever Faster Changing Arctic: Making the Most of Our Collective Research Efforts

8. Outlook

The initial phase of the AMBON project has provided us with invaluable insights about the requirements of a powerful and sustainable biodiversity observing network in the Arctic Chukchi Sea. The conclusions we have drawn for a "Sustainable AMBON" take into account system characteristics (distribution patterns, environmental context, spatial scale of sampling needed for various ecosystem components, power of change detection), the data needs for endusers (e.g., resource managers, indigenous peoples of the Arctic), logistical constraints (high cost of work in the Arctic, limited seasonal access), the sensitivity of the Arctic ecosystem (sampling for scientific purposes also impacts the system, requiring coordination of efforts among research projects), and the potential contributions to a national MBON concept. These ideas have culminated in a proposal to NOPP for the continuation of AMBON in a sustainable manner (subsequently funded under NOPP as NOAA NA19NOS0120198 and BOEM NT-20-10). In this follow-on project we capitalize on collaborative efforts in Arctic research to maximize scientific reward of breadth of data collection and cost efficiency.

Keeping these constraints in mind, the following elements are examples that were included in the consideration of designing the sustainable AMBON project:

- Collect biodiversity data on ecosystem elements that align with the Essential Ocean Variable (EOV) /Essential Biodiversity Variable (EBV) concepts to harmonize sampling with other national and global programs
- Specifically ensure that common ecosystem elements for a national MBON are collected – as much as possible or feasible – for example, eDNA
- Coordinate field efforts with other ongoing research projects in the Arctic to optimize resources for sample collection (e.g., Chukchi Ecosystem Observatory (CEO), Distributed Biological Observatory (DBO), ECO FOCI, etc.)
- Employ an adaptive strategy where the AMBON project will collect samples that are complementary to those that are being collected through these other projects
- Aim to collect biodiversity information in both the southern and northern Chukchi Sea study region
- Sample coverage should extend in in the cross-shelf direction
- If not all ecosystem elements can be collected annually, sampling of long-lived, little mobility species such as benthos can potentially be sampled over longer than annual scales (e.g., every other year)
- Assess if some year-round biodiversity sample/data collection can be automated, e.g., through coordination with the CEO (e.g., phytoplankton biodiversity over the annual scale from sediment traps or eDNA from water collections)
- Explore the ability to use seascapes to relate to biodiversity of different ecosystem elements – seascape detection in the Arctic is more limited in the Arctic than other regions because of seasonal ice cover and cloud cover
- Continue dedication to open access data provision
- Continue to engage with resource managers on the national and international scale to ensure biodiversity data inform resource planning
- Continue meaningful engagement with local stakeholders, specifically Arctic indigenous groups, in a two-way learning exchange

In addition, we have used the insights from the AMBON project to leverage funds to increase instrumentation to help observe biodiversity year-round. Specifically, we were able to obtain funding from the Alaska Ocean Observing System (AOOS) for a water sampler for the CEO mooring, which will allow us to collect water samples year-round to analyze for eDNA. This will complement more spatially broad eDNA ship-based sampling during the summer. In addition, AOOS funded a benthic camera, which will be moored to the CEO and allow us to observe a small part of the seafloor year-sound for movement of benthic taxa. We currently treat epibenthic invertebrates and demersal fishes mostly as a static entity, so this camera system will be able to allow us to gain a better appreciation of spatial turnover of biodiversity in the epibenthos.

We also were able to obtain funding from the Coastal Marine Institute (CMI, a joint finding source from BOEM and the University of Alaska Fairbanks) to undertake a new synthesis of observation data from the Chukchi Sea (CMI M20AC10010/ BOEM AK-19-02-09). This synthesis includes observations from several ongoing project, mainly the AMBON project and the CEO mooring but also including other datasets such as from the DBO. In addition to undertaking new data syntheses, we also aim to refine our conceptual understanding of the system, which is especially important in these times of increasing environmental changes in the Arctic. The combination of summer season, station-based measurements (AMBON) with year-round mooring based observations (CEO) provide an unprecedented opportunity to advance our understanding of the Chukchi Sea ecosystem. Combined the two programs together comprise an experienced team of multi-disciplinary and multi-sector partners involved in a wide variety of Arctic biodiversity and ecosystem measurements to coordinate and contribute to such a synthesis effort. Currently, participating scientists and stakeholders plan for a synthesis retreat at the end of October 2021.

9. Budget table

The following table was provided by the UAF Office of Grants and Contracts Administration. Funds for this project have been expended in full. Shifts in spending between proposed and actual budget categories were less than 10% of the total funding amount.

Category	Adjusted Budget	Expenditures	Balance
Student Aid	$ 81,200.00	$ 27,248.00	$ 53,952.00
Commodities	$ 64,502.01	$ 58,839.73	$ 5,662.28
Capital Expenditures	$ 24,000.00	$ 24,336.04	$ (336.04)
F & A Cost	$ 551,480.31	$ 668,786.68	$ (117,306.37)
Personal Services Costs	$ 529,077.06	$ 628,021.68	$ (98,944.62)
Staff Benefits	$ 163,921.94	$ 166,382.71	$ (2,460.77)
Contractual Services	$ 2,470,915.69	$ 2,323,018.40	$ 147,897.29
Travel	$ 93,801.99	$ 82,265.76	$ 11,536.23
Total	**$ 3,978,899.00**	**$ 3,978,899.00**	**$ -**

Department of the Interior (DOI)

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM's Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).