

A Sustainable, Integrated AMBON in the Chukchi Sea



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ABOUT THE COVER

Aurora (northern lights) in the night sky above young sea ice (pancake ice) in the northeastern Chukchi Sea in November 2021. Photo by Seth Danielson.

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Table of Contents

List of Abbreviations and Acronyms	viii
1 Project Goals	1
2 Background	2
3 Science Accomplishments	4
3.1 Field work	4
3.2 Physical environment	6
3.3 Primary production and phytoplankton community	10
3.4 eDNA	12
3.5 Zooplankton	16
3.6 Benthos	17
3.6.1 Macrofauna	17
3.6.2 Trends in epibenthic biomass, community composition and diversity	18
3.6.3 Year-round epibenthic imagery	21
3.7 Fish	22
3.7.1 Essential Fish Habitat	22
3.7.2 Fish functional diversity	23
3.8 Seabirds	25
3.9 Marine Mammals	31
3.9.1 Pinnipeds – walrus and bearded seals	32
3.9.2 Cetaceans – bowhead and beluga whales	33
3.9.3 Soundscapes	34
3.10 Seascapes	36
3.11 Diversity assessment across ecosystem components	39
4 Stakeholder Engagement and Networking	42
5 Publications and Presentations	43
5.1 Publications	43
5.2 Major Reports	45
5.3 Presentations	45
6 Datasets	49
7 References	50

List of Figures

Figure 1. Essential Ocean Variables (EOV) as defined by the Global Ocean Observing System (GOOS). EOVs shaded in yellow were collected specifically for the AMBON project. EOVs shaded in blue were collected as part of the joint AMBON, CEO and DBO projects.	2
Figure 2. Map of the Chukchi Sea study region, indicating major water masses as well as the Distributed Biological Observatory stations sampled during the 2020 and 2021 cruises.	3
Figure 3. September 2014 to August 2024 temperature and salinity at the CEO mooring site in the northeastern Chukchi Sea. For reference, shading shows the record length daily climatology of each parameter, presenting the long-term average against which annual trends can be compared. The black box indicates years that were sampled under this project.	6
Figure 4. Near-bottom hydrographic properties observed in October 2020 (Norseman II cruise).	7
Figure 5. Near-bottom properties observed in November 2021 (Sikuliaq cruise SKQ202115S).	8
Figure 6. Sediment conditions found in October 2020 (Norseman II cruise) along the sampled DBO survey lines: Station map (top left), carbon stable isotope values (bottom left), sediment chlorophyll-a (top right), and total organic carbon (TOC, bottom right).	9
Figure 7. Sediment conditions found in November 2021 (Sikuliaq cruise SKQ202115S) along the sampled DBO survey lines: Station map (top left), integrated water column chlorophyll-a values (bottom left), sediment chlorophyll-a (top right), and total organic carbon (TOC, bottom right).	10
Figure 8. Water column chlorophyll a (left panel) and nutrient conditions (left plots, from top to bottom: silicate, nitrate + nitrite, total inorganic nitrogen) in the southern Chukchi Sea at one of the DBO long-term survey transects, collected during the Norseman II cruise in October 2020. From Cooper and Grebmeier (2022). White contour lines indicate salinity levels.	11
Figure 9. Diatom composition of 24 samples collected by the CEO sediment trap from August 2015 to August 2016.	11
Figure 10. Seasonal patterns of diatom abundance over one-year sediment trap deployment from August 2015 to August 2016.	12
Figure 11. Bargraph of COI marker detections along DBO lines in October 2020 and November 2021, representing relative abundances of taxa. Each bar in the figure represents a sample, but samples are grouped by DBO line for better overview. Data for each station also are presented for surface versus deep samples.	13
Figure 12. Non-metric multidimensional scaling (nMDS) plots of eDNA samples analyzed with the COI marker, color-coded by DBO line affiliation (left plot) and by sampling depth stratum (right plot). Data from both sampling years were combined for this analysis.	14
Figure 13. Bargraph of MiFish marker detections along DBO lines in October 2020 and November 2021, representing relative abundances of taxa. Each bar in the figure represents a sample, but samples are grouped by DBO line for better overview. Data for each station also are presented for surface versus deep samples.	15
Figure 14. Distribution of marine mammals (cetaceans only) using eDNA samples taken in 2021 at stations in the water column (no samples taken at stations in the southern Bering Sea, that are shown on the sampling map).	15
Figure 15. Abundance of some key holoplankton zooplankton components across years, compared for DBO lines 1-4, which were sampled during the field work in this AMBON project as well as a previous AMBON project and other collaborative projects. The month in which collections occurred in each year is indicated.	17
Figure 16. Benthic macrofauna abundance (left) and biomass (right) during the October 2020 cruise.	18

Figure 17. Predicted biomass across the Chukchi Sea, derived from VAST model output, averaged for each study year (left) and spatially for each year (right). Biomass on the left are the VAST means and standard errors of the annual estimates of epifaunal biomass (kg). The circles on each map indicate observed biomass and the colors are the density distributions (in kg/km ²) of the epibenthos.....	19
Figure 18. Epibenthic community composition across sampling years in the non-metric multidimensional scaling plot. Vector circle indicates taxa that were driving the distribution of annual community structure, where the individual vector length is relative to the maximum predictor strength (circle size).	20
Figure 19. Modeled Delta diversity index for each sampling year. Darker colors refer to lower and lighter colors to higher Delta values.....	20
Figure 20. Predicted (VAST model) Delta diversity index for each grid cell for each year, plotted against latitude. Years are indicated in gray scale, with darker shades for later years. The blue line indicates the significant linear regression line over latitude (p<0.001).	21
Figure 21. Examples of images retrieved from the benthic camera in 2024. Left: The seafloor is densely covered with brittle stars. Middle: A snow crab and a nemertean worm move through the image. Right: A dead jellyfish has sunk to the bottom and provides detrital food for benthic consumers.....	22
Figure 22. Haul locations for all stations sampled by bottom trawl or Issac-Kidds Midwater Trawl (IKMT) in the US portion of the Chukchi Sea between 1990 and 2019 by cruise. Data from these cruises were included in the database.....	22
Figure 23. Fish taxonomic trait cluster distribution and functional composition of three major fish assemblage clusters in the Chukchi Sea. Maps show the annual distribution of the three clusters across the Chukchi Sea.....	24
Figure 24. Community-weighted mean redundancy analysis (CWM-RDA) that ordines the clusters (colored dots) with specific traits (black font boxes) and to environmental conditions (red font boxes).....	25
Figure 25. Violin plot showing the range and distribution of stable isotope ratios of A) carbon ($\delta^{13}\text{C}$), B) nitrogen ($\delta^{15}\text{N}$), and C) oxygen ($\delta^{18}\text{O}$) in the breast and wing feathers of short-tailed shearwaters.....	26
Figure 26. Isotopic niche size for breast and wing feathers of short-tail shearwaters, indicating a larger niche size for wing feathers.....	27
Figure 27. Posterior distribution of the probabilistic niche overlap (%) within a 95% isotopic niche region for breast and wing feathers of short-tailed shearwaters. Solid turquoise lines represent the posterior means, while dashed turquoise lines indicate the 95% credible intervals.	28
Figure 28. Foraging areas delineated based on regions where geolocator-tagged short-tailed shearwaters foraged.	29
Figure 29. Range and distribution of stable isotope ratios of carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$), and oxygen ($\delta^{18}\text{O}$) in short-tailed shearwaters.	30
Figure 30. Mean stable isotope values ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$) of short-tailed shearwaters (wing feathers), grouped by summer foraging region, as determined from geolocator tracking data. The colors represent different foraging regions.	31
Figure 31. Spectrograms of characteristic signals produced by walrus (top panel) and bearded seals (bottom panel) used to detect the presence of each species. Note the different time axes. .	32
Figure 32. Acoustic detections of walrus (top panel) and bearded seals (bottom panel) with sea ice concentration (orange line) at the Chukchi Ecosystem Observatory from 2015-2020, since 2019 as part of the AMBON program. The orange line represents sea ice cover, the blue peaks indicate vocalizations. Red stars and arrows indicate missing data.	33

Figure 33. Acoustic detections by day in comparison to sea ice concentration (orange line) are shown for bowhead whales (top panel) and belugas (bottom panel) at the Chukchi Ecosystem Observatory from 2015-2020. Red stars indicate missing data. 34

Figure 34. Annual long-term spectral average for 2016-2020 from the passive acoustic recorder at the Chukchi Ecosystem Observatory, as part of the AMBON project. The 'dots' around 3 kHz and 5 kHz are artefacts from the co-located ADCP on the moorings. Example signals are indicated. 35

Figure 35. Seascape classifications separately for the northern (top panel) and southern (bottom panel) Chukchi Sea between 2003 and 2021. 36

Figure 36. Sea ice cover (left panel) and ice edge blooms (right panel) in the northern and southern Chukchi Sea. The decrease in sea ice cover in the north is associated with an increase in ice edge blooms, but less in the south..... 37

Figure 37. Dynamic seascape classifications for July 2017 from: The Global model (left), the Regional model (middle), and the Physics only model (right). Rectangles denote regions where seascape output or model fields were extracted. Seascape classifications given as color bars below each model output with the most relevant classifications given to the right. Model and remotely sensed data were specifically extracted for the regions indicated by the boxes, of which the two boxes in the Chukchi Sea represent the AMBON study region. Seascape classifications as in Fig. 35. 38

Figure 38. Changes in seascape areal extent through time (2002-2018) for: Northern Chukchi Sea (top) and Southern Chukchi Sea (bottom) from the regional model (left) and the physics only model (right). Seascape classification colors as in Fig. 35. 39

Figure 39. Sea surface temperatures (top row) and bottom water temperatures (bottom row) at sampling stations during AMBON cruises in 2015 (first column) and 2017 (second column), as well as the difference between the two years (third column). Positive values (red) indicate higher temperatures in 2017. 40

Figure 40. Spatial gradients in local species richness of six assemblages sampled during AMBON 2015 (left column) and 2017 (center column), with lighter (yellow) colors denoting higher species richness. Shading in the right column shows the differences in species richness between the two years (2017-2015 values), with blue colors indicating higher richness in 2015 (cold year). 40

Figure 41. Species richness against temperature, with estimated linear relationships and 95% confidence bands by year (blue for 2015, orange for 2017). Bottom temperatures were used for benthic communities (macro-infauna, epibenthos, demersal fish), and sea surface temperatures for other assemblages. 41

List of Tables

Table 1. Stable isotope ratios (mean \pm standard deviation) for breast and wing feathers of short-tailed shearwaters.....	27
Table 2. Stable isotope ratios (mean \pm standard deviation) for short-tailed shearwater wing feathers in different foraging areas, based on geolocator tracking data.....	30
Table 3. Datasets archived during the AMBON project.	49

List of Abbreviations and Acronyms

AMBON	Arctic Marine Biodiversity Observing Network
AOOS	Alaska Ocean Observing System
AVISO	Satellite altimetry data
BOEM	Bureau of Ocean Energy Management
CEO	Chukchi Ecosystem Observatory
CTD	Conductivity Temperature Depth instrumentation
COVID	Coronavirus disease
CWM-RDA	Community-weighted mean redundancy analysis
DBO	Distributed Biological Observatory
ECCO2	Remotely sensed sea surface temperature and salinity
EcoFOCI	Ecosystems and Fisheries Oceanography program (NOAA)
eDNA	Environmental deoxyribonucleic acids
EFH	Essential fish habitat
EOV	Essential Ocean Variables
GOOS	Global Ocean Observing System
IEA	Integrated Ecosystem Assessment
IOOS	Integrated Ocean Observing System
LTSA	Long-term spectral averages
MBON	Marine Biodiversity Observing Network
NCEI	National Centers for Environmental Information
NCIS	Northern Chukchi Integrated Study
nMDS	Non-metric multidimensional scaling
NSF	National Science Foundation
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Ocean Partnership Program
NPRB	North Pacific Research Board
OBIS	Ocean Biodiversity Information System
PAROMS	Pan-Arctic Regional Ocean Model
SAS	Synoptic Arctic Survey
TOC	Total organic carbon
USCGC	United States Coast Guard Cutter
VAST	Vector Autoregressive Spatio-Temporal model

1 Project Goals

Unprecedented changes are occurring in the Arctic and affect all components of Arctic marine ecosystems, including humans. However, consistent, long-term observations for planning and adaptation are not fully in place in the Arctic Ocean. The current Arctic Marine Biodiversity Observing Network (AMBON) project is a sustainable approach to biodiversity observing in the Chukchi Sea and serves as one component in a developing National Marine Biodiversity Observing Network (MBON) program. Grounded in the concept that sustained biodiversity across ecosystem components is critical for maintaining healthy ecosystem functions, this project is using strategic collaborations to build an observing network in the Arctic Chukchi Sea. We work with other research and monitoring projects to expand the collection of otherwise un-observed Essential Ocean Variables (EOV, Table 1) and share core environmental collections as a sustainable way to conduct logistically costly observations in the Arctic. This approach ensures that biodiversity is measured across multiple ecosystem components – from microbes to whales – and observations are being related to a full suite of environmental measurements that help understand diversity patterns in space and time. One collaborative focus of this study was to link to and enhance a stationary mooring array in the northern Chukchi Sea, the Chukchi Ecosystem Observatory (CEO), which provides year-round environmental and biological observations. This installation included a moored water sampler that collects year-round samples that can be used for eDNA analyses, a sediment trap to sample phytoplankton, and a passive acoustic recorder to observe vocalizing marine mammal presence. The other main collaboration focus was with the Distributed Biological Observatory (DBO), which is a change detection array with fixed observing lines across the northern Bering and the Chukchi Sea (and beyond) in areas of high biological productivity and activity. This collaboration allowed us to maximize the information that can be gained per station for a more complete ecosystem understanding. Finally, we explored the application of remotely sensed seascapes in the Arctic, where ice cover and strong seasonality can limit the application of traditional remotely sensed parameters. Data archiving and publication is a strong focus of this project, using standard data formats (metadata, Darwin Core) to publish data on the MBON Portal, archive data at the National Centers for Environmental Information (NCEI), and provide data to the Ocean Biodiversity Information System (OBIS). This report presents highlights of all data streams that were collected but not all data are comprehensively presented here. Complete data availability is listed at the end of the report (section 6).

This project partnered with end user groups to integrate AMBON data with specific management needs in the Arctic. One partnership was with NOAA's Integrated Ecosystem Assessment (IEA) program to help develop and inform an IEA for the Chukchi Sea. This project also has tight links to BOEM's Environmental Studies Program, even though there are currently no active lease areas in the region; however, the information gained from this project is of general importance for understanding outer continental shelf ecosystem functioning in Alaska waters. Similarly, while there is currently no active commercial fishery in the Arctic, the changes that are occurring in the Chukchi Sea provide important context and forecast for the fished Bering Sea system and for the possible expansion of commercial fisheries into the central Arctic. We have strong ties to the North Pacific Fishery Management Council through its statistical committee and provide this important Arctic perspective for the subarctic regions. Beyond the Arctic regional scale, the sustainable AMBON project collaborates with other funded MBON projects (x-MBON) to continue to work on developing and testing common concepts for the national MBON plan.

Physics	Biogeochemistry	Biology and Ecosystems
Sea state	Oxygen	Phytoplankton biomass and diversity
Ocean surface stress	Nutrients	Zooplankton biomass and diversity
Sea ice	Inorganic carbon	Fish abundance and distribution
Sea surface height	Transient tracers	Marine (turtle,) bird, mammal abundance and distribution
Sea surface temperature	Particulate matter	Live coral
Subsurface temperature	Nitrous oxide	Seagrass cover
Surface current	Stable carbon isotopes	Macroalgal cover
Subsurface currents	Dissolved organic carbon	Mangrove cover
Sea surface salinity	Ocean colour (<i>under development</i>)	Microbe biomass and diversity (*emerging)
Subsurface salinity		Benthic invertebrate abundance and distribution (*emerging)
Ocean surface heat flux		

Figure 1. Essential Ocean Variables (EOV) as defined by the Global Ocean Observing System (GOOS). EOVs shaded in yellow were collected specifically for the AMBON project. EOVs shaded in blue were collected as part of the joint AMBON, CEO and DBO projects.

2 Background

The Chukchi Sea is a shallow Arctic inflow shelf that is strongly connected and influenced by processes and waters in the Bering Sea (Carmack and Wassmann 2006). Because of sea surface height differences, water typically flows northward from the Bering Sea, through the Bering Strait, carrying significant amounts of heat, freshwater, and nutrients into the Chukchi Sea (Clement Kinney et al. 2014, Danielson et al. 2014). Waters entering the Chukchi Sea through Bering Strait typically divert into three main water mass branches. Low salinity, low nutrient and warmer water hugs the Alaskan coast as the Alaskan Coastal Water (Fig. 2). The central Chukchi Shelf Current splits into a central branch that exhibits intermediate salinity and nutrient concentrations, and a western branch dominated by hydrographic conditions of waters originating in the Gulf of Anadyr with extremely high nutrient concentrations (Danielson et al. 2020, Clement Kinney et al. 2022) (Fig. 2).

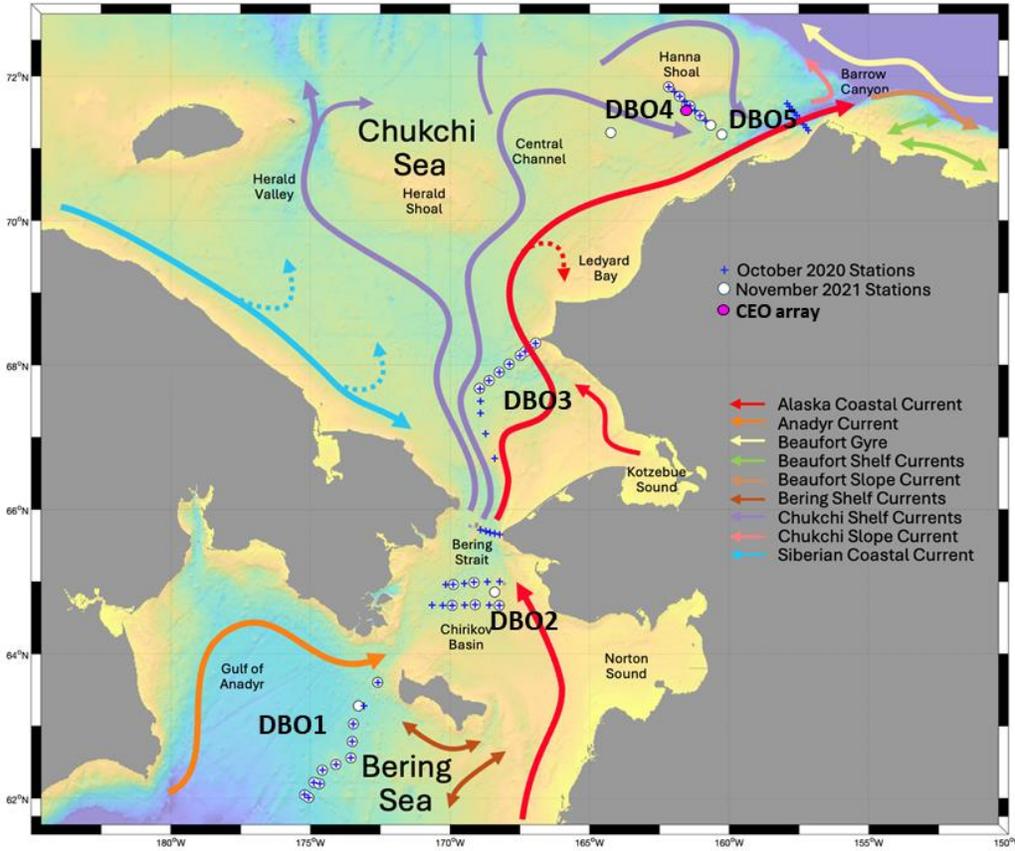


Figure 2. Map of the Chukchi Sea study region, indicating major water masses as well as the Distributed Biological Observatory stations sampled during the 2020 and 2021 cruises.

The Arctic environment is changing at a rate four times faster than the global average (Ratanen et al. 2022). In the marine environment in the Chukchi Sea, these changes manifest in a significant decrease in seasonal sea ice cover and a subsequent increase in heat content from summer and fall warming (Danielson et al. 2020, Polyakov et al. 2020). Changes in temperature and sea ice cover also influence the carbonate system in the Chukchi Sea, including low pH and aragonite undersaturation, which typically present stressful conditions for marine organisms (Hauri et al. 2014). Both the pelagic and benthic system are under tight environmental controls, although the specific environmental drivers differ between these major ecosystem compartments (Pisareva et al. 2015, Hunt et al. 2016).

Changes in the Chukchi Sea environment have documented consequences for multiple ecosystem components. For example, according to general expectations, primary production increased significantly over the past two decades, based on longer open water periods, increased nutrient influx, and expansion of nutrient-rich water mass distribution (Lewis et al. 2020, Zheng et al. 2021, Lee et al. 2023). Consequently, zooplankton communities have also increased in biomass, with a significant influx and expansion of boreal species on the Chukchi shelf with a relaxation of low temperature control (Ershova et al. 2015, Xu et al. 2018, Spear et al. 2020). Similar shifts were found in higher trophic levels. Sea ice loss, warming waters and increased Pacific water transport flow have altered larval fish community distributions between 2010 to 2019, with the boreal larval fish assemblage expanding northward and offshore and a northward contraction of the Arctic assemblage (Axler et al. 2023). Similarly, time of sea ice retreat prominently influenced the distribution of the Arctic-affinity adult demersal fish community, while a boreal community correlated significantly and positively with summer bottom temperature in an

analysis of trawl data from 1990 and 2013 (Nishio et al. 2020). While earlier ice retreat and longer open water season seems to initially benefit Arctic cod, a key species in the Arctic food web, long-term changes in prey quantity and quality and effects on reproductive success suggest that warming effects will have negative repercussions on Arctic cod (Gonzalez et al. 2023). Long-term benthic macrofaunal biomass trends are variable, with decreases in the southern Chukchi Sea since the 1970s and a more rapid decline starting in the late 1990s across the entire Chukchi Sea; however, some hotspot regions first increased in biomass with subsequent declines only after 2012 (Grebmeier et al. 2015a, b). Slight increases in macrofaunal biomass have been reported between 2000-2013 in the southern Chukchi Sea as well as some northward increases in benthic macrofaunal biomass (Grebmeier et al. 2018, Waga et al. 2020). The only published record of long-term trends in epifauna showed a drastic decline in epibenthic biomass from 2004 to 2017 based on few stations solely in the southeastern Chukchi Sea (Huntington et al. 2020).

The longer open-water period and changes in prey field have also led to changes in sentinel seabird species at the upper trophic levels (Gall et al. 2016). Specifically, in a comparison between the 1970s with the 2010s, previously dominant piscivorous seabirds were replaced with a higher abundance of planktivorous species. Subarctic marine mammals have been increasingly detected on the Chukchi Sea shelf, notably killer and humpback whales, with some Arctic species (e.g., bowhead whales, grey whales) contracting further north to avoid competition or seeking better feeding grounds (Stafford et al. 2022). Massive aggregations of walrus on land are now a commonplace as their typical sea ice resting platform has retreated off the Chukchi shelf (Fishbach et al. 2016). Some of these ecosystem components that are characterized by small body size and responsiveness to water flow (zooplankton, larval fish) or are characterized by high mobility (adult fish, seabirds, mammals) respond to changes in environmental conditions very quickly, while the more stationary and long-lived benthos likely responds on longer timescales to environmental change (Mueter et al. 2021a).

Many of these longer-term changes in the environment and, subsequently, in the biota, can only be detected with long-term monitoring so that interannual variation can be filtered from the long-term trend. Also, focusing on biodiversity trends in the system can be a powerful tool to infer ecosystem resilience and efficiency. Systems with higher diversity are proposed to foster stable and productive ecosystems because of the high number and complexity of ecosystem functions that a larger number of coexisting species can support (Duffy et al. 2017). Therefore, a goal of the AMBON project was to collect information on and continue long-term records across ecosystem components of the Chukchi Sea, to further explore aspects of diversity, and provide useful and reliable data to decision makers and stakeholders.

3 Science Accomplishments

3.1 Field work

The AMBON project did not have standalone, dedicated field work support but rather worked in collaboration with other Arctic programs to accomplish its new field collections. Field work during the project period became extremely challenging because of the global pandemic. We were successful however with cruises in 2020 and 2021 as part of this project. In **2020**, AMBON was part of two research cruises. Seabird observations were conducted during the EcoFOCI/ NCEI cruise on the *R/V Oscar Dyson* from 24 August – 24 September 2020, starting in Seattle and ending in Kodiak. The original plan had been to conduct all AMBON-related field work during this cruise but NOAA excluded all AMBON participants after one participant's COVID test returned as (false) positive. The seabird observation data collected during the cruise contributed to both the AMBON project as well as a US Fish and Wildlife

project funded by Bureau of Ocean Energy Management, project AK-17-03, Marine Distribution and Abundance in Offshore Waters (M17PG00039). AMBON PIs then put much effort into planning a smaller cruise in 2020 for the AMBON, CEO and DBO goals; efforts especially by PIs Grebmeier, Cooper, Danielson and Iken were successful in gathering financial support for this from BOEM, NOAA, and NPRB. The cruise occurred 3 – 22 October 2020, in and out of Nome on the R/V *Norseman II* (Service Vessels of Alaska). AMBON-related tasks (collaboratively with other projects) completed during that cruise were hydrography (Danielson), eDNA sampling (Galaska), zooplankton sampling (Hopcroft), macrobenthic sampling (Grebmeier), sediment characteristics (Cooper), and the turn-around of AMBON-supported CEO instrumentation, such as the passive acoustic recorder (Stafford).

In **2021**, we again planned a NOAA-led joint cruise of multiple partner projects but, unfortunately, the NOAA lowest bid policy led to the chartering of a supply vessel, the M/V *Discovery*, which proved to be unsuitable for oceanographic work, particularly in Arctic waters. In addition, a COVID outbreak among the crew forced the research cruise to be aborted a few days into the cruise. We spent much time and effort to gather sufficient support and funds to stage another cruise to accomplish some of the essential program objectives. Ultimately, we mobilized a cruise aboard the R/V *Sikuliaq* in November 2021 that was a collaboration among four projects, AMBON, the CEO, the DBO, and NOAA's Ecosystems and Fisheries Oceanography (EcoFOCI) programs. The Alaska Ocean Observing System (AOOS), the North Pacific Research Board (NPRB) and AMBON through the National Ocean Partnership Program (NOPP), with additional funds from the National Science Foundation (NSF), the Bureau of Ocean Energy Management (BOEM), and NOAA's Integrated Ocean Observing System (IOOS), all contributed financially to the cruise. The cruise (SKQ202115S) departed Nome on 7 November and returned to Nome on 16 November 2021. Although this was much later in the year and limits comparability with other sampling years, the cruise afforded a rare opportunity to document late fall conditions in the Chukchi Sea study region. The collaborative team on board again sampled AMBON-related components of hydrography (Danielson), sediment characteristics (Cooper), eDNA sampling (Galaska), zooplankton (Hopcroft), macrobenthic sampling (Grebmeier), as well as undertook the retrieval of AMBON-supported CEO instrumentation (passive acoustic recorder, (Stafford). Because of heavy sea ice conditions, the CEO mooring (including AMBON supported instruments) that had been recording for the past year could not be recovered during that cruise, but a new mooring set was deployed.

In **2022**, we partnered with the CEO, the DBO, and the Synoptic Arctic Survey (SAS) projects to conduct limited field work for the AMBON project. Logistically supported by the USCGC *Healy* via NSF support, the cruise took place 31 August– 29 October 2022. The cruise went all the way to the North Pole, but only sampled limited stations on the Chukchi shelf. However, the CEO mooring array was retrieved and redeployed, which carries a number of AMBON-supported instrumentation. Specifically, we retrieved the passive acoustic recorder that records marine mammal sound, the sediment trap that provides samples for phytoplankton composition, and the water sampler, which provides samples for eDNA analysis. The mooring array that was then redeployed carried these three instruments but also a new benthic camera system, which was acquired with leveraged funds from the AOOS to support AMBON goals.

In summary, much time and effort were spent during the project period in organizing and coordinating field work. Specific recognition for field work organization and coordination goes to AMBON PIs Drs. Jackie Grebmeier and Seth Danielson, who were instrumental in the success of making these cruises happen. The COVID pandemic caused tremendous problems for field work but other problems developed from chartering an inadequate vessel. For the future, we will continue to seek creative and different strategies to conduct Arctic field work and collaboration among field programs in effective ways.

3.2 Physical environment

Physical environmental data that cover some of the **physical and biochemical EOVs** (temperature, salinity, oxygen, various biochemical measures) were produced from CTD station casts and from year-round recordings from the CEO mooring array in the northeastern Chukchi Sea (Fig. 2). These year-round data have been analyzed and provided insights on the seasonal workings of the northeastern Chukchi shelf and the Chukchi ecosystem. Near-bottom temperatures underneath the sea ice rise above the freezing point as early as April in years that the Chukchi shelf is extremely warm (Fig. 3). Warm years also show subsurface temperatures that are 2-6 °C warmer than the freezing point for multiple months in a row. Such temperatures have implications for the seafloor community.

Temperatures on the shelf were colder than typically observed in the summer, although the mid-shelf region in October 2020 was surprisingly warm (Fig. 4, 5). The typically warm and low-salinity Alaska Coastal Current (Fig. 2) was less developed in October 2020 than in November 2021, but that likely reflects interannual variability and not a seasonal signal.

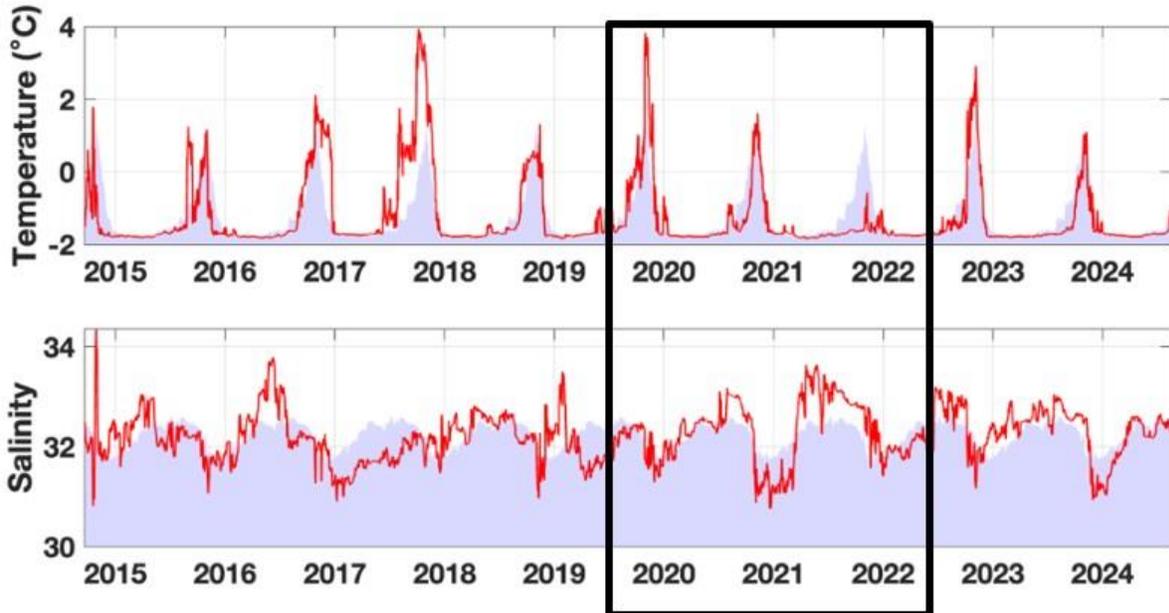


Figure 3. September 2014 to August 2024 temperature and salinity at the CEO mooring site in the northeastern Chukchi Sea. For reference, shading shows the record length daily climatology of each parameter, presenting the long-term average against which annual trends can be compared. The black box indicates years that were sampled under this project.

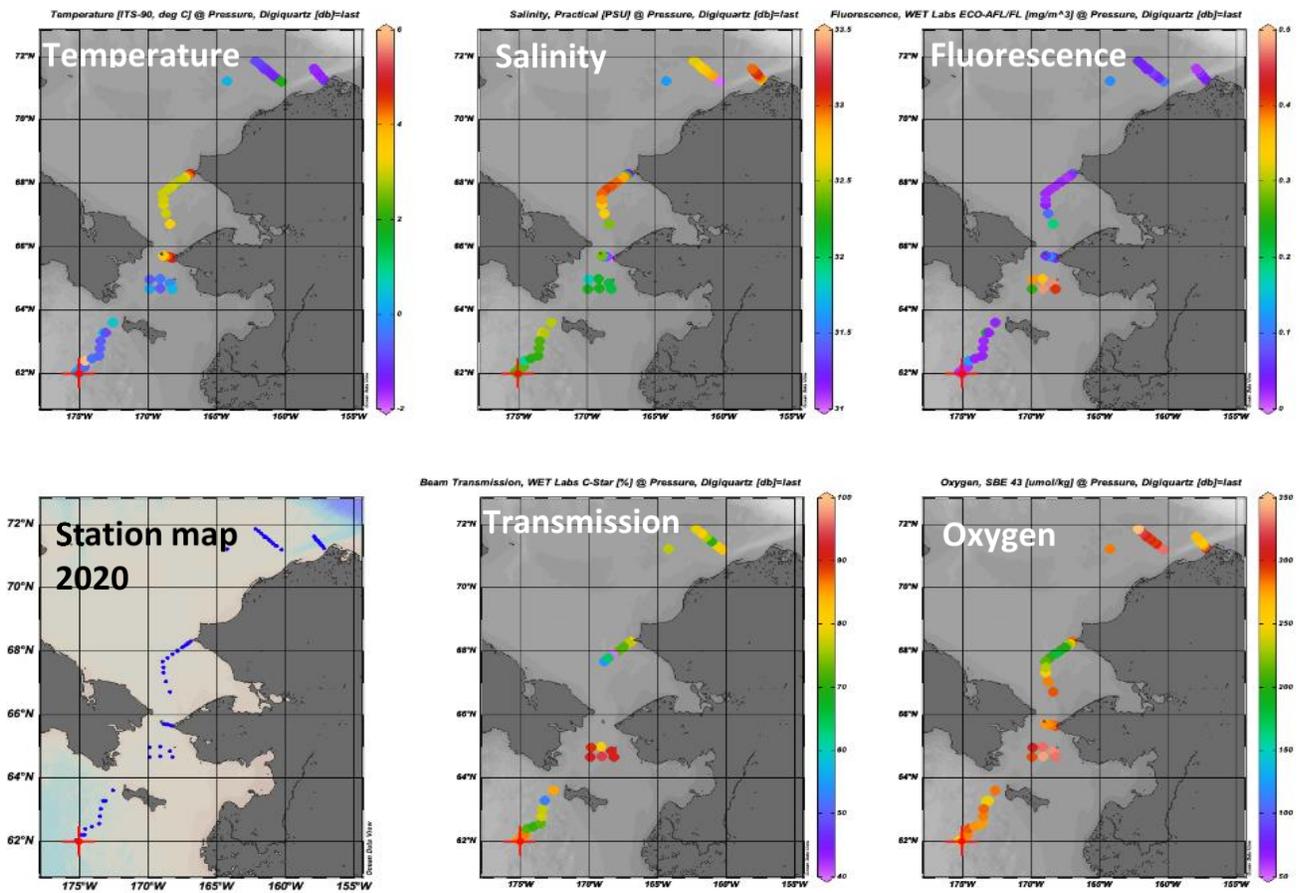


Figure 4. Near-bottom hydrographic properties observed in October 2020 (Norseman II cruise).

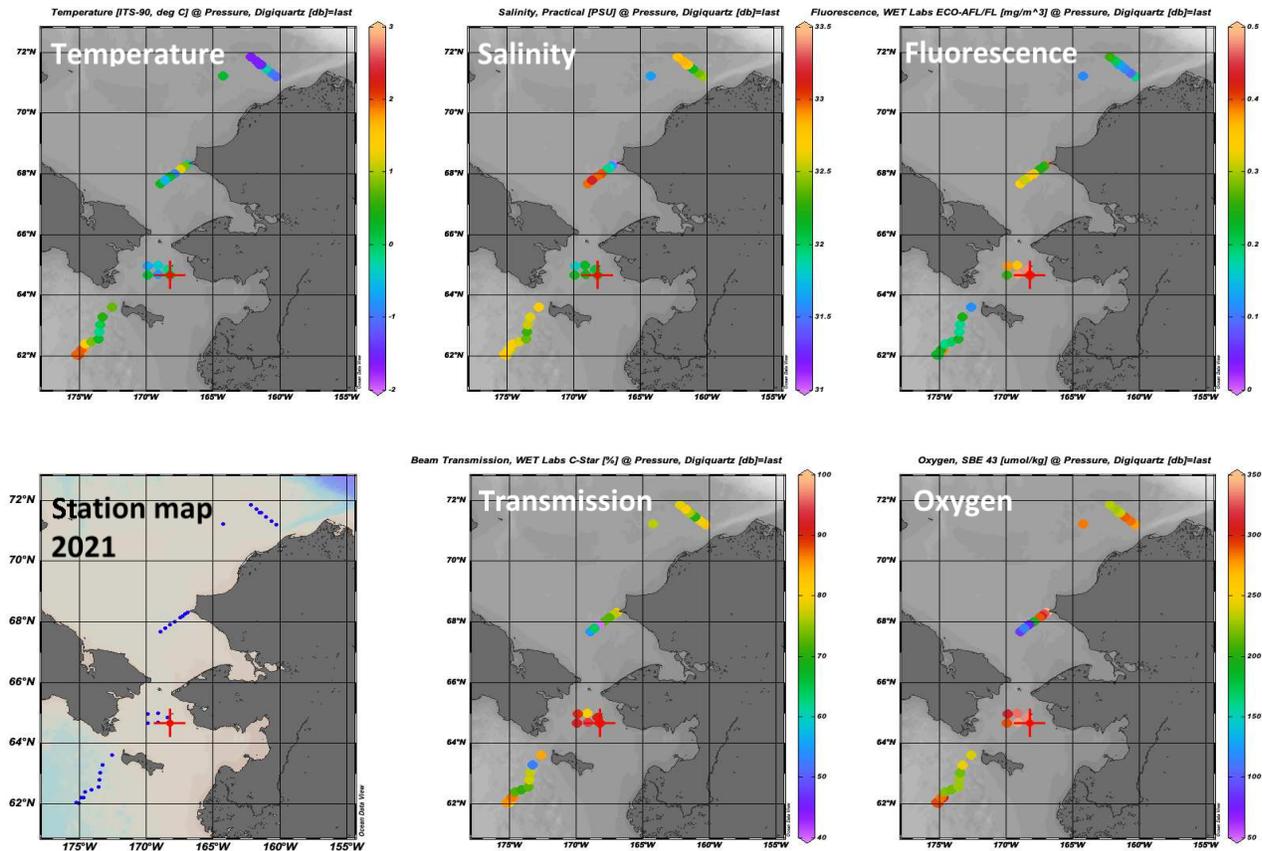


Figure 5. Near-bottom properties observed in November 2021 (Sikuliaq cruise SKQ202115S).

Surface sediment sampling from benthic grabs provided important environmental information on sediment characteristics. In 2020 (October), we saw relatively high amounts of sediment chlorophyll-a and total organic carbon (TOC), potentially reflecting the high phytoplankton levels observed during this late fall cruise (see below for phytoplankton) (Fig. 6). It seems this fall production continues to sink to the seafloor and accumulates there to serve as a food bank for the benthic community over the winter (Schollmeier et al. 2018). This opportunity to observe conditions in the late fall confirm that the Arctic system is not as devoid of food after the short summer production period as traditionally assumed. The relatively high (enriched) $\delta^{13}\text{C}$ values just below and above Bering Strait may indicate high processing and reworking of the sediments in those regions.

The benthic habitat characteristics in the fall 2021 (November) cruise confirmed similar patterns as were found for fall 2020, but even later in the year (Fig. 7). In 2021, we did not find any evidence for lingering fall phytoplankton blooms in the water column, but sediment chlorophyll was high, as was TOC, indicating that pelagic production had sunken to the seafloor and that food availability on the seafloor was high at the time of sea ice formation.

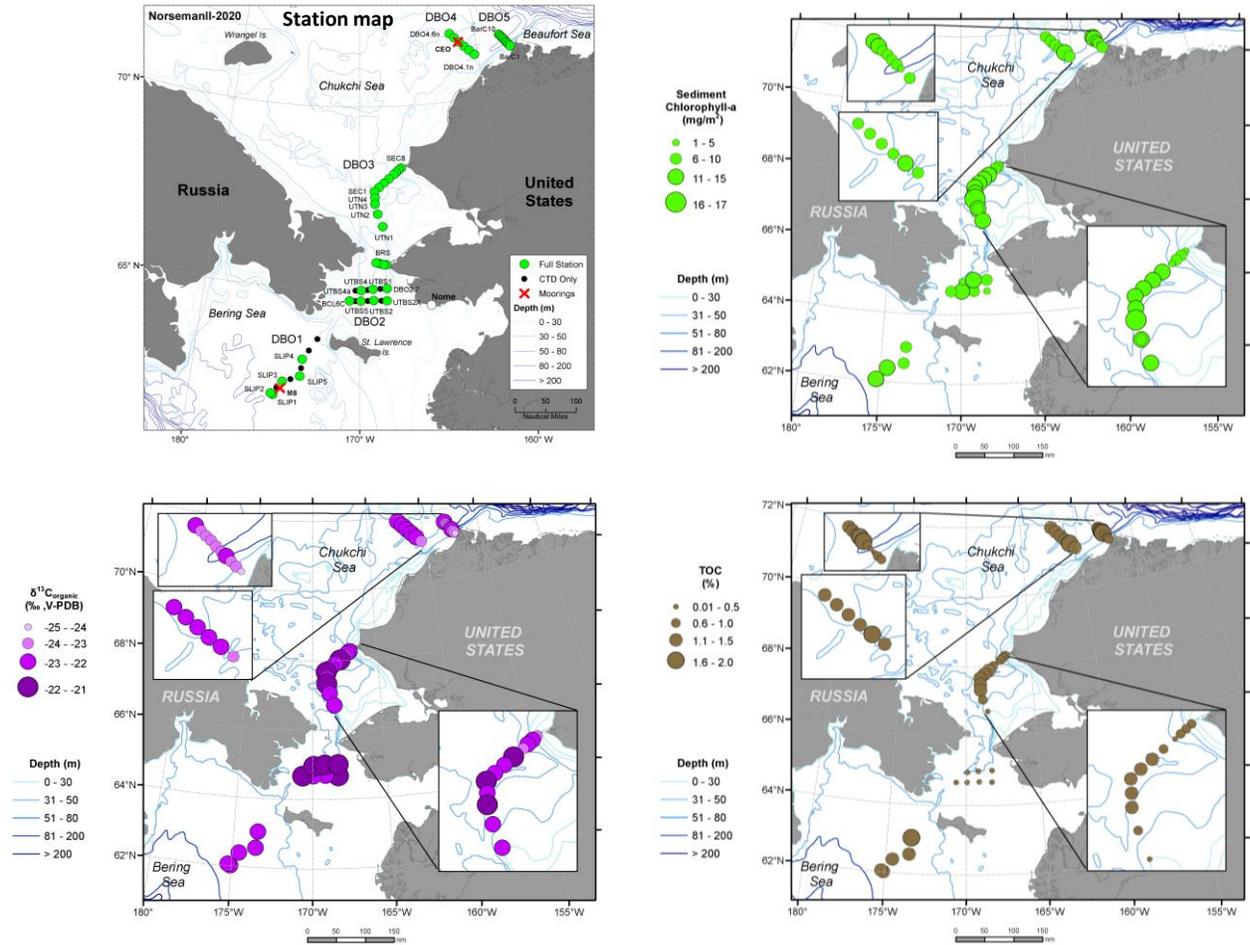


Figure 6. Sediment conditions found in October 2020 (Norseman II cruise) along the sampled DBO survey lines: Station map (top left), carbon stable isotope values (bottom left), sediment chlorophyll-a (top right), and total organic carbon (TOC, bottom right).

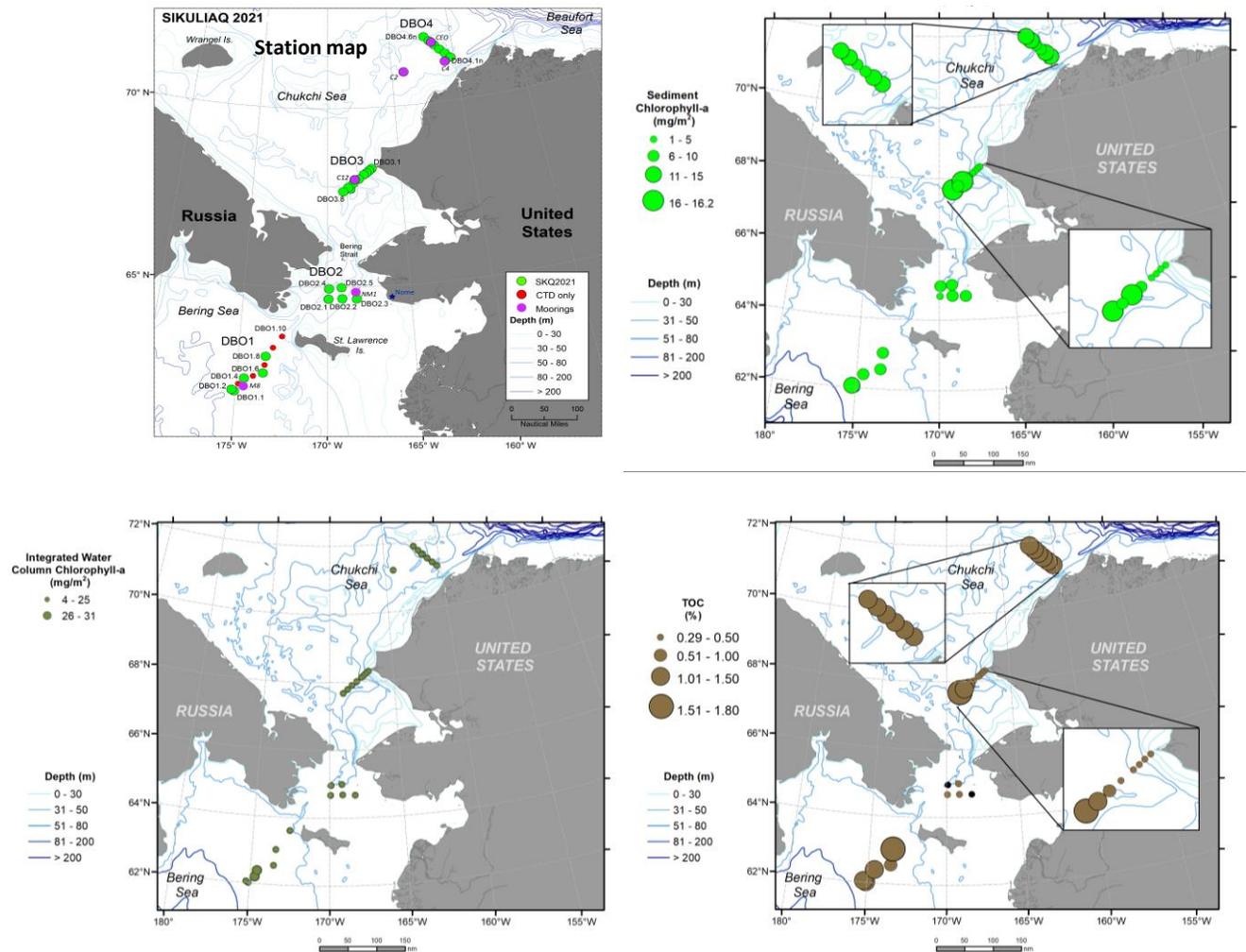


Figure 7. Sediment conditions found in November 2021 (Sikuliaq cruise SKQ202115S) along the sampled DBO survey lines: Station map (top left), integrated water column chlorophyll-a values (bottom left), sediment chlorophyll-a (top right), and total organic carbon (TOC, bottom right).

3.3 Primary production and phytoplankton community

The cruises and CEO deployments allowed us to obtain some new data on the EOV “**Phytoplankton biomass and diversity**”. The DBO-AMBON-CEO collaborative *Norseman II* cruise in October 2020 allowed a glimpse into later season conditions than are typically collected on the Chukchi Sea shelf. One of the surprising observations was that we found higher than expected chlorophyll-*a* concentrations in the water column (Fig. 8, Cooper and Grebmeier 2022). While chlorophyll-*a* concentrations were generally less than in a typical summer (e.g., July) scenario, they were higher than expected for this time of year and in some locations in the southern Chukchi Sea even higher than in the summer. Nutrients were concentrated towards the bottom and at higher concentrations (Fig. 8) than typically found in the summer, possibly a result of remineralization from the sediments. However, the combination of high nutrients with elevated water column chlorophyll-*a* concentrations, in a water column structure that is less stratified than in the summer, suggests that these conditions are favorable for fall bloom scenarios. While primary production in the Arctic with climate change is typically predicted to increase based on reduced sea ice

cover, this may not (only) manifest in the total production in the summer but especially an extension of the growing period late into the fall. Wind mixing in the fall is likely to introduce nutrients back into the upper water column, thus enabling fall production.

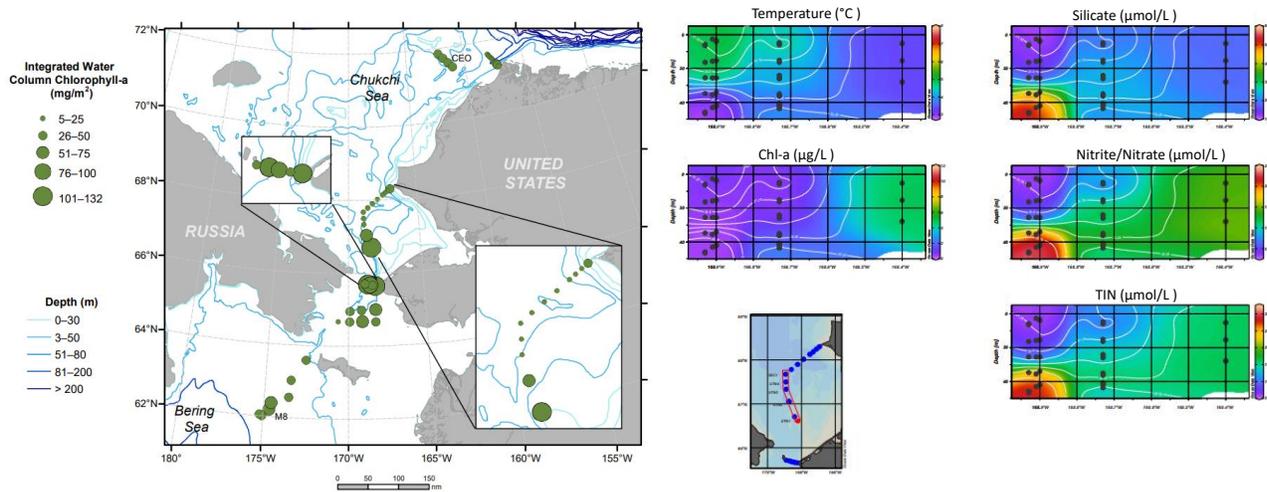


Figure 8. Water column chlorophyll a (left panel) and nutrient conditions (left plots, from top to bottom: silicate, nitrate + nitrite, total inorganic nitrogen) in the southern Chukchi Sea at one of the DBO long-term survey transects, collected during the Norseman II cruise in October 2020. From Cooper and Grebmeier (2022). White contour lines indicate salinity levels.

The sediment trap located on the CEO mooring is a good source of information on year-round phytoplankton composition. Part of this AMBON project support was used to assist with the analysis of archived samples (from 2015-2016) from the sediment trap on the CEO mooring in the northeastern Chukchi Sea as part of a doctoral dissertation (Nesterovich 2019). A total of 138 diatom species were identified, with about 10 species making up the majority of the community (Fig. 9). The various species followed a distinct seasonal succession with some species peaking in fall (e.g., *Nitzschia longissima*) while others peaked in early summer after the sea ice break-up (e.g., *Fragilariopsis oceanica*) (Fig. 10).

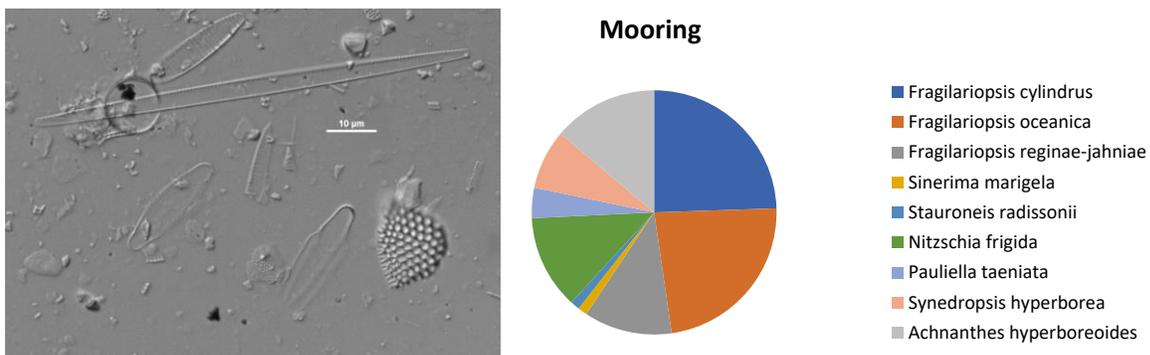


Figure 9. Diatom composition of 24 samples collected by the CEO sediment trap from August 2015 to August 2016.

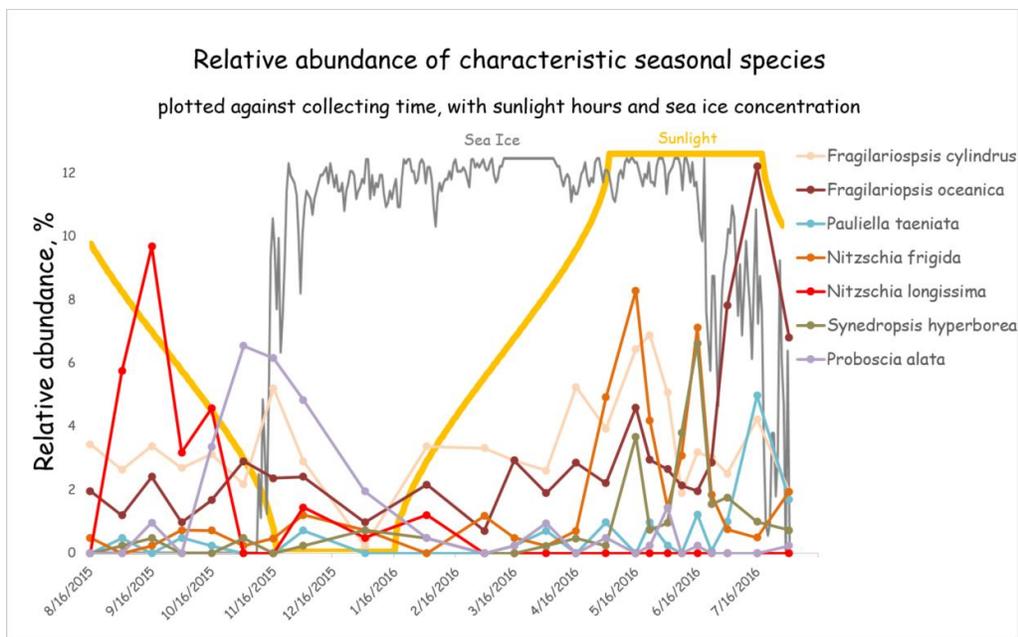


Figure 10. Seasonal patterns of diatom abundance over one-year sediment trap deployment from August 2015 to August 2016.

3.4 eDNA

eDNA samples were collected from water samples taken during CTD casts during the October 2020 field season (R/V *Norseman II*) and the November 2021 field season (R/V *Sikuliaq*). For the 2020 collections, samples were analyzed for 18Sv4 (phytoplankton), Parada16S (microbes), Machida18S (metazoan/plankton), COI (metazoan), and MiFish (fish/marine mammals). For the 2021 collections, samples were analyzed for 18Sv4 (phytoplankton), 18Sv9 (phytoplankton), Parada16S (microbes), COI (metazoan), ITS1 (*Pseudo-nitzschia*), Machida18S (metazoan/plankton), and MiFish (fish/marine mammal). This array of primers provided an opportunity to target multiple ecosystem components, including a cover the new **emerging EO** “**Microbe biomass and diversity**”.

Samples were taken from “surface” (between 3-10 m depth, depending on weather and the ability to obtain a reliable sample in shallow depth due to wave action), and “deep”, which is 2-3 m off the bottom, depending on station depth. One 1-L water sample was collected per depth from the CTD Niskin bottle array and filtered onto Sterivex™ filters, preserved in 90-proof ethanol and then kept frozen until analysis.

The 18Sv4 primer set targets primarily single-celled eukaryotic organisms (e.g., phytoplankton, dinoflagellates, diatoms, and haptophytes) and amplifies the Small subunit ribosomal ribonucleic acid (SSU rRNA) 18S v4 gene in eukaryotes (Stoeck et al. 2010, Balzano et al. 2015). The 18Sv9 primer set targets single-celled eukaryotic organisms (e.g., phytoplankton, dinoflagellates, diatoms, and haptophytes) and amplifies the Small subunit ribosomal ribonucleic acid (SSU rRNA) 18S v9 gene in eukaryotes (Amaral-Zettler et al. 2009). The ITS1 primer set specifically targets *Pseudo-nitzschia* spp. diatoms, and is based on amplifying the internal transcribed spacer 1 (ITS1) gene in eukaryotes (White et al. 1990, Sterling et al. 2022). *Pseudo-nitzschia* can be a source of domoic acid and a cause of harmful algal blooms (Bates et al. 1998). The Parada16S is universal, amplifying organisms from across the tree of life, and is based on the amplification of the 16S rRNA v4-v5 region (Parada et al. 2016). However,

with the limited DNA quantity of invertebrates/vertebrates in the water column, this primer set most effectively targets microbes (e.g., Bacteria, Archaea, phytoplankton, single celled organisms), and is not reliable for monitoring multicellular organisms. The Machida18S primer set targets metazoan organisms (e.g., mollusks, arthropods, and vertebrates) by amplifying the Small subunit ribosomal ribonucleic acid (SSU rRNA) 18S v8 gene in eukaryotes (Machida and Knowlton 2012). The COI primer set targets metazoan organisms (e.g., mollusks, arthropods, and vertebrates) by amplifying the cytochrome c oxidase subunit I (COI) mitochondrial gene in eukaryotes (Folmer et al. 1994, Leray et al. 2013). The MiFish primer set targets vertebrates organisms (e.g., fishes, marine mammals, birds) by amplifying the 12S mitochondrial ribosomal RNA gene in vertebrates (Miya et al. 2015, Sales et al. 2019). It is important to note that, aside the target taxa, other taxa are also regularly detected by each of these markers. Those detections are typically less reliable and need to be considered with care. Here, we only present a subset of the data collected for eDNA analysis that are already fully analyzed. While all samples have been

Within each of the study years, we observed a both some consistencies and differences across the two depth strata as well as between years. For the COI primer, Interannual differences were noticeable, where in 2020 generally relatively fewer arthropods and annelids were detected than in 2021, while there were relatively more Synurophyceae in 2021 (Fig. 11). The patterns among surface and deep samples at DBO lines in both years were relatively consistent for some DBO lines; for example, relatively high abundance of Phaeophyceae and Haptophyta at the DBO2 line in 2020 was consistent between surface and deep samples, as was the high relative abundance of Synurophyceae at DBO3 in both surface and deep samples. The consistency between depth strata is likely related to mixing from the dynamic environment at the generally shallow Chukchi Sea shelf stations, although strong stratification can occur at some stations. However, at other stations, the two depth strata showed differences, for example the high detection of annelids in deep samples along the DBO4 but not at the surface samples (Fig. 11). The difference among years is likely related to the difference in sampling month between the two years. While both cruises occurred in the fall, particularly the abundance of microalgae is expected to change rapidly as the late fall season and sea ice formation begin (November).

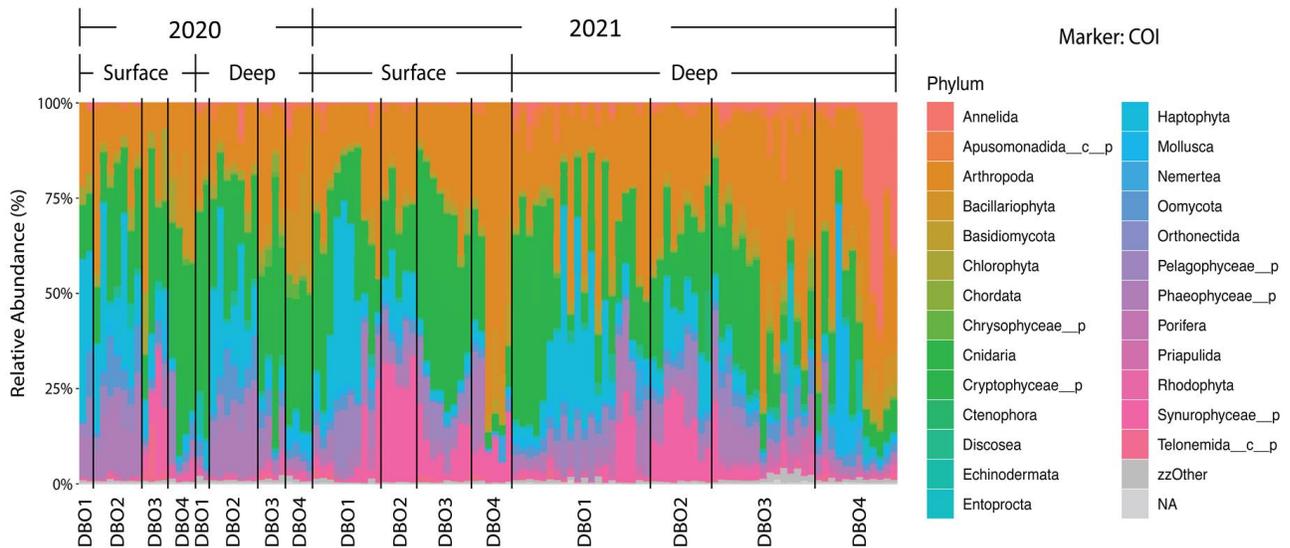


Figure 11. Bargraph of COI marker detections along DBO lines in October 2020 and November 2021, representing relative abundances of taxa. Each bar in the figure represents a sample, but samples are grouped by DBO line for better overview. Data for each station also are presented for surface versus deep samples.

The slight differences in DBO line taxon composition based on the COI marker were also visible when using a non-metric multidimensional scaling (nMDS) plot (Fig. 12). While there was much overlap in the samples across the sampling lines, there was a noticeable progression from DBO1 to DBO4. This pattern very much reflects also latitudinal gradient from south to north, respectively. And while major taxa detected in surface and deep samples at a station were often similar, there were some differences, as can be seen in the partial separation of deep and surface samples in multivariate ordination space (nMDS, Fig. 12).

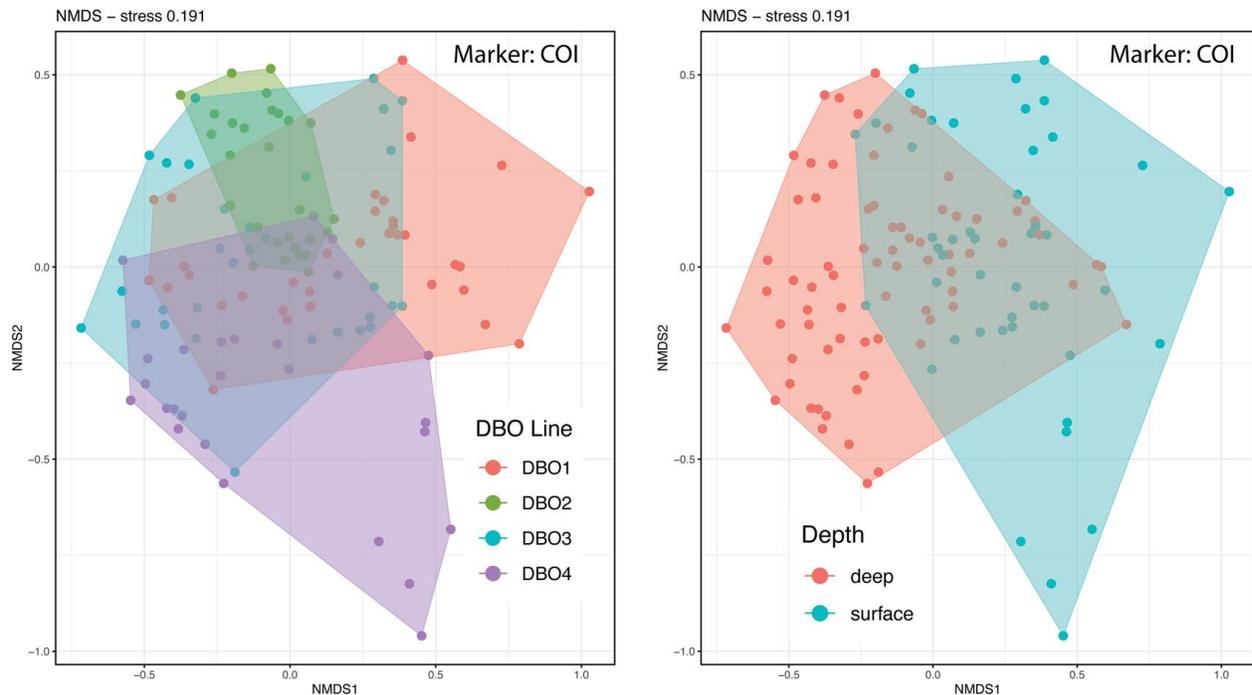


Figure 12. Non-metric multidimensional scaling (nMDS) plots of eDNA samples analyzed with the COI marker, color-coded by DBO line affiliation (left plot) and by sampling depth stratum (right plot). Data from both sampling years were combined for this analysis.

Here, we also present results on the MiFish primer results, focusing on detections of fishes and marine mammals. Similar to the COI detections, there were some patterns between the two sampling strata at the various DBO lines, as well as some interannual differences. Most notable is the much larger detection of gadids in surface samples than deep samples in both years (Fig. 13). Conversely, pleuronectids were generally more common in deep samples, although that difference was more pronounced in 2021. Interannually, the 2020 surface samples had more abundant detections of clupeids than the 2021 surface samples, while the deep samples in 2021 had more detections of ammodytids and stichaeids than the deep samples in 2020. The repeated detection of ammodytids in surface samples in 2020 was surprising, given the strong bottom-association of these fishes (sand lance). Generally, the differences among the sampling strata were more obvious in 2021 compared to 2020, but this may be due to the larger number of samples collected in 2021. Marine mammal detections occurred, particularly common were belugas (*Monodontidae*) but seals, walrus and baleen whales were also occasionally detected (Fig. 13). The compilation in Fig. 14 shows the detection of marine mammals in 2021 based on a variety of primers. While MiFish was one of the more reliable primers for marine mammal detection, we recommend further exploration of marine mammal detections with specific markers, such as D-Loop (Baker et al. 2018) with an additional gel-cleaning step or the newer primer MarVer (Valsecchi et al. 2020).

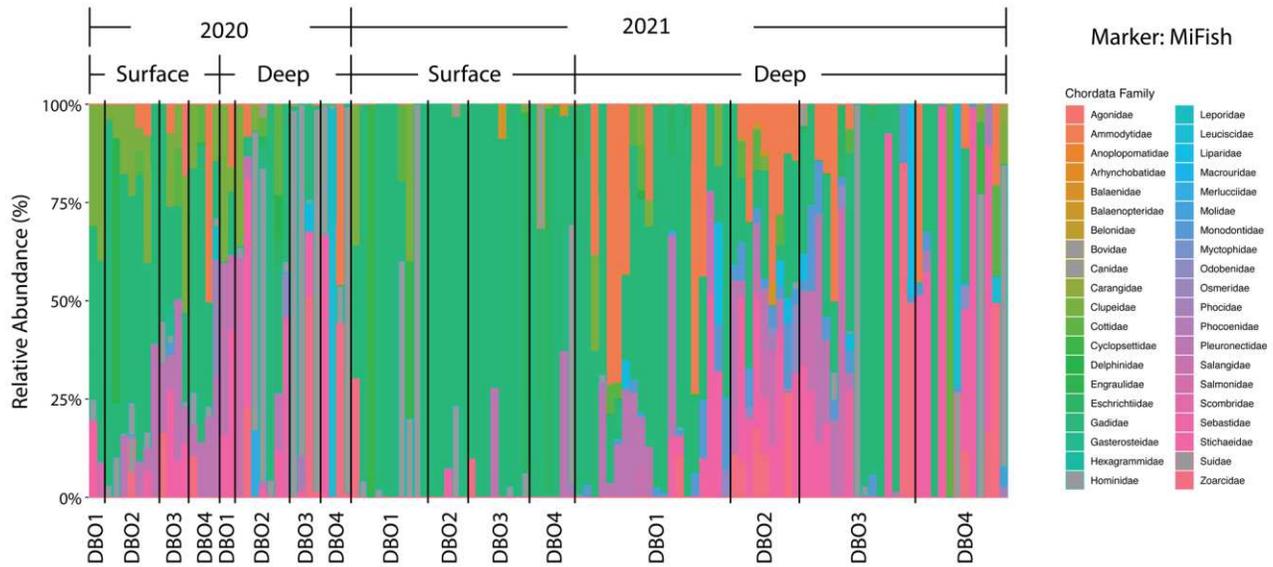


Figure 13. Bargraph of MiFish marker detections along DBO lines in October 2020 and November 2021, representing relative abundances of taxa. Each bar in the figure represents a sample, but samples are grouped by DBO line for better overview. Data for each station also are presented for surface versus deep samples.

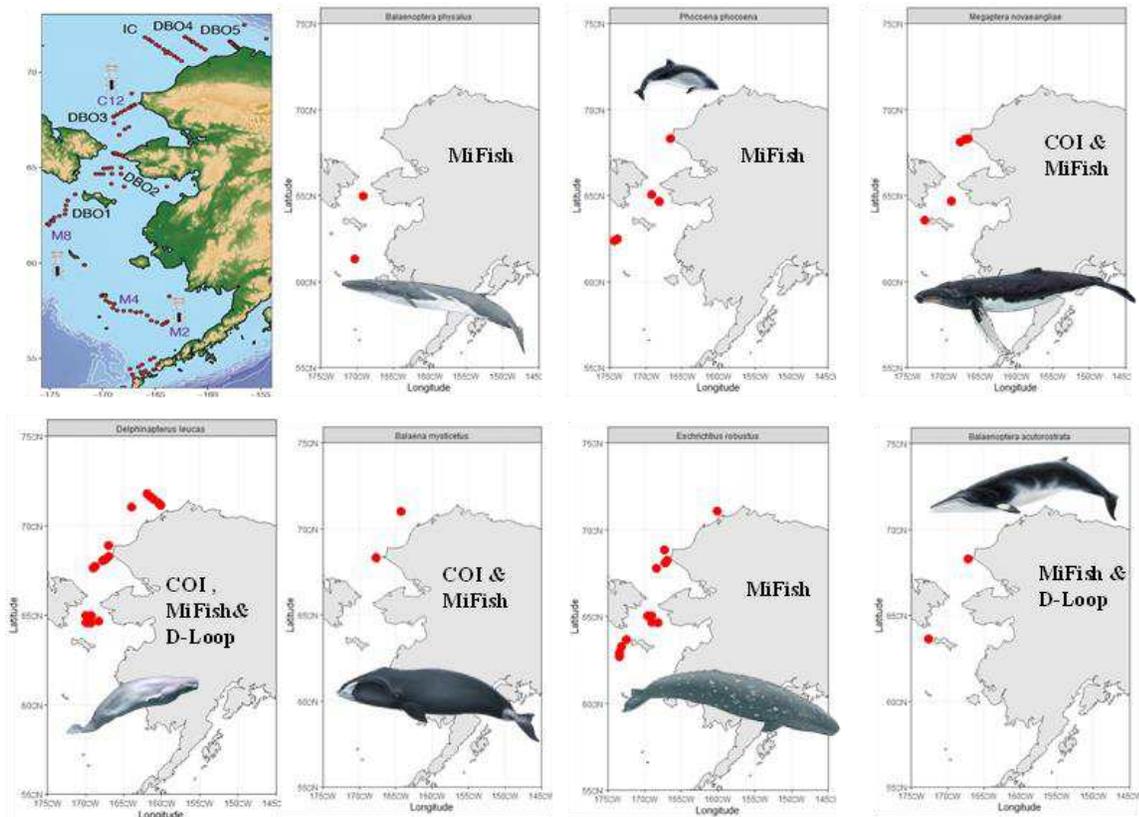


Figure 14. Distribution of marine mammals (cetaceans only) using eDNA samples taken in 2021 at stations in the water column (no samples taken at stations in the southern Bering Sea, that are shown on the sampling map).

3.5 Zooplankton

Zooplankton sampling during this phase of AMBON occurred on the two late-fall cruises conducted in 2020 and 2021. Here, we have focused our consideration of patterns to the (log-transformed) mean of each DBO line sampled during these cruises; as strong latitudinal and cross shelf gradients are known to exist in these communities (e.g., Eisner et al. 2013, Questel et al. 2013, Ershova et al 2015), overall shelf considerations are difficult with samples with a strong focus on sampling lines. Furthermore, with no (published) sampling having occurred as late as November, we make our comparisons to prior sampling by the AMBON 1 program (August 2015 and 2017) as well as the ASGARD program (June 2017 and 2018) that used identical methodology for collection and analysis. Lastly, we recognize that considerable interannual differences exist in the Chukchi Sea zooplankton community (Questel et al. 2013, Ershova et al 2015, Abe et al. 2020), making comparison seasonal comparisons across years challenging.

Notable differences for our November samples include a reduction in the abundance of some zooplankton taxa, a pattern particularly pronounced for meroplanktonic larvae of benthic species, as well as larval stages of holoplanktonic crustaceans such as copepods and crustaceans. For copepod species such as *Calanus*, which rely on the overwintering diapause at depth, an observed reduced abundance and accumulation of late-stage copepodites was expected (Fig. 15). In contrast, the numerically dominant shelf-dwelling calanoid copepod, *Pseudocalanus*, did not show a significant reduction in numbers (Fig. 15). Abundance of a small cyclopoid copepod, *Oithona*, showed an increasing trend. For both these latter genera, animals were spread relatively evenly across copepodite developmental stages, suggesting recruitment to the adult population was still ongoing. It seems that these smaller copepods remain on the shelf until they likely mostly die off during winter. The chaetognath *Parasagitta*, a copepod predator, showed relatively stable abundance across seasons, likely since some of the copepod species were also abundant, providing a continued food source into the late fall. The pteropod *Limacina* was unexpectedly more abundant in November than prior month, but it is unclear if this was driven by seasonal or interannual differences. Lastly, the abundances of both common euphausiid species (*Thysanoessa* spp.) were much higher in the fall than observed in prior seasons (Fig. 15). This latter observation may help explain how large planktivorous baleen whales continue to find an abundance of prey to support them until they are forced out of the region by seasonal ice formation.

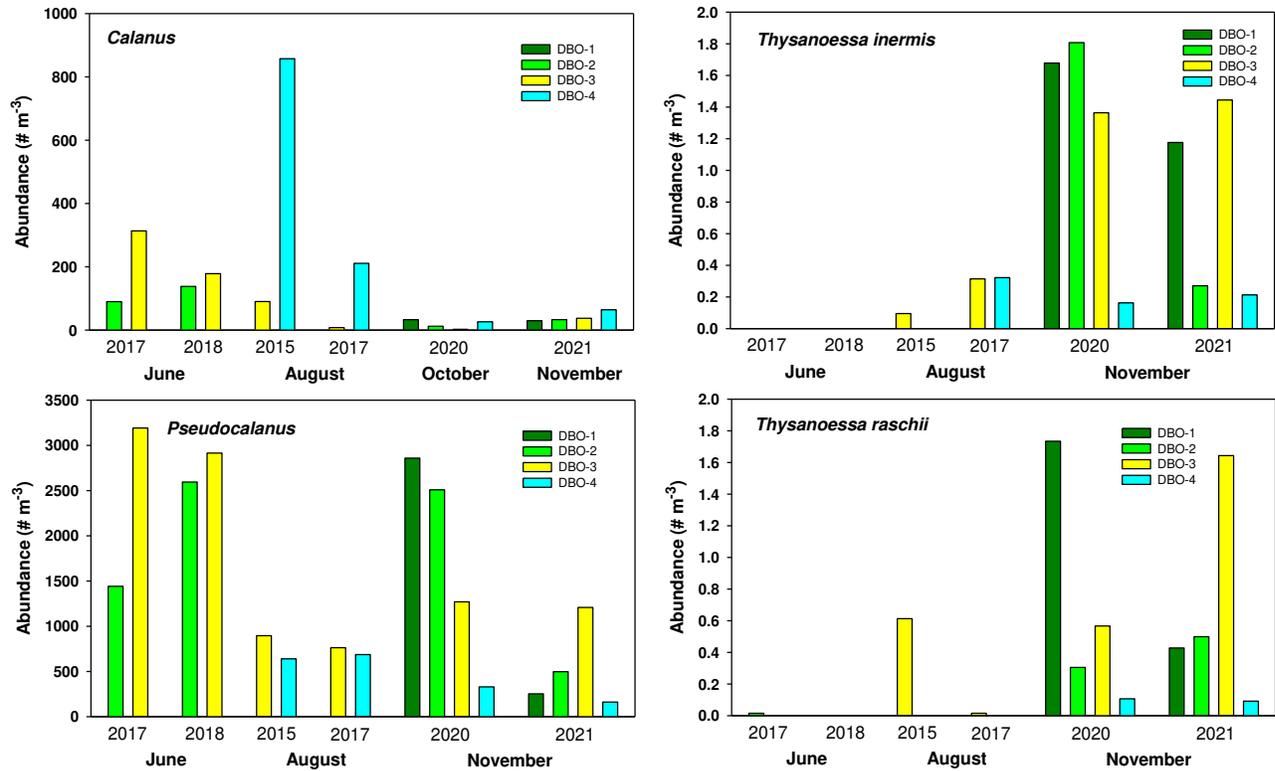


Figure 15. Abundance of some key holoplankton zooplankton components across years, compared for DBO lines 1-4, which were sampled during the field work in this AMBON project as well as a previous AMBON project and other collaborative projects. The month in which collections occurred in each year is indicated.

3.6 Benthos

Benthic studies are an essential part of AMBON because of the strong pelagic-benthic coupling and the importance of the benthic system for upper trophic levels (e.g., walrus, bearded seals, grey whales, diving ducks), which, in turn, are of strong subsistence interest for the Indigenous communities along the Chukchi Sea shore. This contributes to the emerging EOY “**Benthic abundance and distribution**”. This includes mostly work on epifauna, but in collaboration with the DBO, also on macro-infauna (following: macrofauna).

3.6.1 Macrofauna

Macrobenthic collections were completed using standardized van Veen grab samples during both cruises (2020 and 2021) as a collaboration with the DBO project. Benthic biomass in fall 2020 was high, similar to other times of the year sampled in previous years, reflecting the longevity of benthic fauna that buffers this ecosystem component from immediate responses to changing conditions (Fig. 16). The above-mentioned high sediment chlorophyll-*a* conditions (Fig. 7) also confirm that there is plenty of food for the benthic community and a sharp decline in abundance or biomass is not likely (and was not seen). Regional differences are obvious where some regions were characterized by both high abundance and biomass (southern Chukchi Sea) while other regions, such as the St. Lawrence region and the Chirikov Basin in the northern Bering Sea, had high abundance but low biomass (Fig. 16). These patterns are indicative of the large clam abundance (contributing much to biomass) in the southern Chukchi Sea, while

small polychaetes and amphipods in the northern Bering Sea can be abundant but contribute much less biomass. The samples from the 2021 cruise are still being worked up as it takes much effort to process these macrofauna samples.

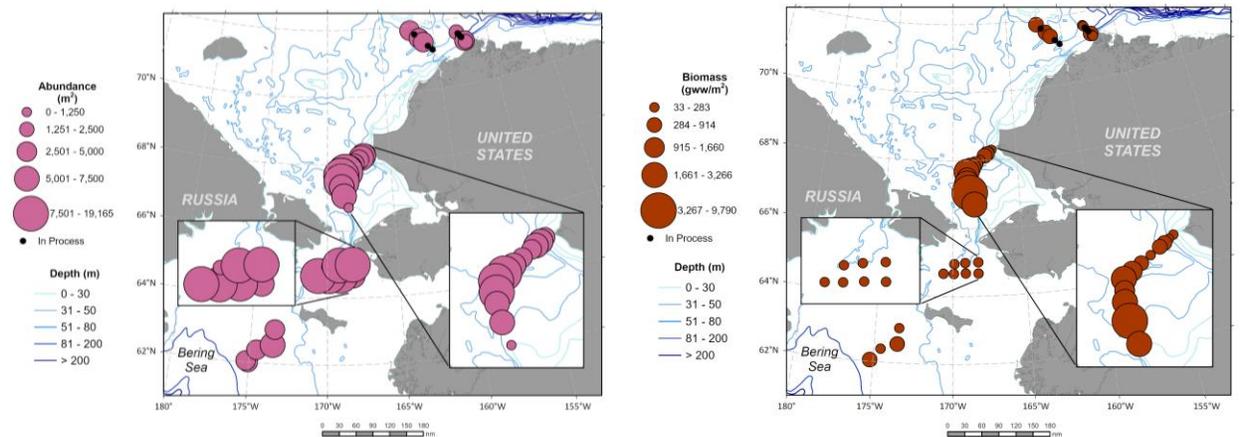


Figure 16. Benthic macrofauna abundance (left) and biomass (right) during the October 2020 cruise.

3.6.2 Trends in epibenthic biomass, community composition and diversity

No new epibenthic trawling occurred through this AMBON project but we used the opportunity to analyze existing long-term data from bottom trawls (incl. from the AMBON 1 project) for an assessment of long-term trends in epibenthic biomass, community composition and diversity. This work is in advanced stages of preparation for publication as Iken, K., Gonzalez, S., Logerwell, E. Trends in epibenthic biomass and community structure in the Chukchi Sea. The journal is TBD but potentially a special issue in Deep-Sea Research II.

Benthic systems on the Chukchi Sea are under environmental controls, in part dynamic factors such as primary production and vertical flux to the bottom, and also more static (slow or non-changing) correlates such as sediment grain size and depth (Feder et al. 1994, Bluhm et al. 2009, Dunton et al. 2014, Schonberg et al. 2014). Advection from the Bering Sea into the Chukchi Sea across the Chukchi shelf is an important driver of benthic communities through the dispersal of propagules (Feng et al. 2021). These environmental controls make the benthic system slightly more stable to environmental change than, for example, zooplankton, but it is reasonable to expect similar trends towards changes in biomass and species composition from borealization for the benthos as for other ecosystem components. Only few analyses have hitherto investigated temporal trends in epifauna in the Chukchi Sea despite the ecological significance of the benthos for ecosystem functioning in pelagic-benthic coupling and as a food source for higher trophic level marine mammal consumers (Bluhm and Gradinger 2008, Moore et al. 2014). A time series from 2004 to 2017 reported a drastic decline in epibenthic biomass but that study was based on very few stations solely in the southeastern Chukchi Sea (Huntington et al. 2020). In a comparison of a colder (2015) and a warmer (2017) year, epibenthic taxon richness was higher in the colder conditions (Mueter et al. 2021a). Serious declines in benthic communities is also known from other Arctic regions, specifically the Barents Sea, but the effects of changes in the environment or the intense commercial trawling activities cannot be separated (Wassmann et al. 2006).

We constrained data to samples taken in the Chukchi Sea between 2009 and 2024. All samples were taken with an identical plumb-staff beam trawl. Due to some taxonomic uncertainties at the species level by different investigators, we standardized data by aggregating all data at the genus level for community composition and diversity assessments. Epifaunal trends in total biomass and spatial biomass distributions across the study region were analyzed using a VAST (Vector Autoregressive Spatio-Temporal) model

(Thorson and Barnett 2017). We determined community composition across all years for the entire study region as well as for select stations repeatedly sampled in the southeastern Chukchi Sea (DBO3 line) and the northeastern Chukchi Sea (DBO4). Diversity was calculated as the Delta index, which is an extension of the Simpson diversity index with an additional scaled metric of taxonomic relatedness of all the taxa in a sample (Warwick and Clarke 1995). The index is not influenced by sampling effort, alleviating potential concerns about differences in trawling times at each station. We also used the VAST model approach to predict trends in Delta diversity across years, and spatially for each year, as well as directly compared the Delta diversity among repeat stations along DBO3 and DBO4.

VAST model results showed an approximately 3-fold decline in overall epifaunal biomass between 2010 and 2012 (Fig. 17). Biomass remained around this lower level for the remaining time series, with a slightly higher peak in 2018 and lowest average biomass in 2023. Biomass declines were most obvious in the northern offshore Chukchi Sea (Fig. 17).

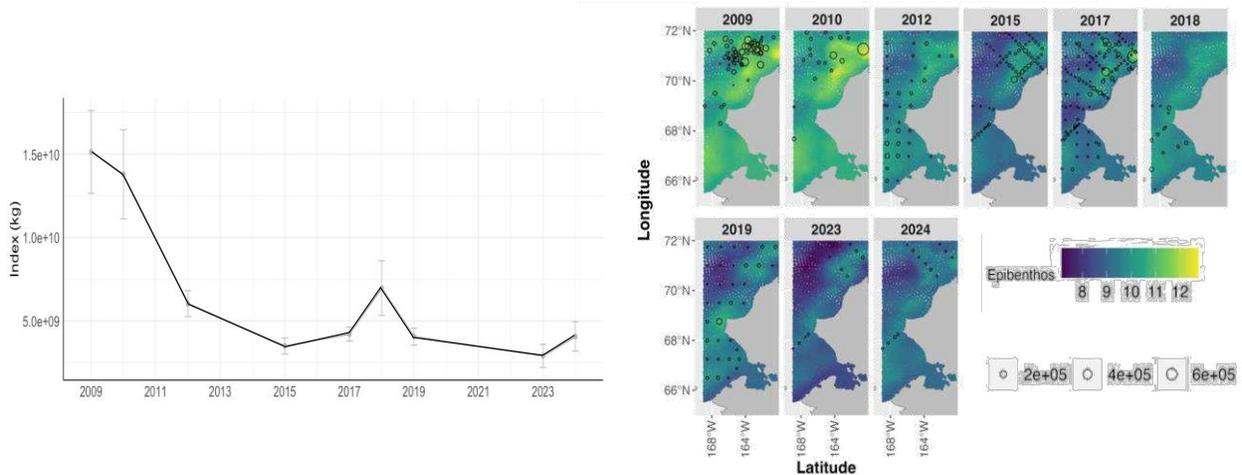


Figure 17. Predicted biomass across the Chukchi Sea, derived from VAST model output, averaged for each study year (left) and spatially for each year (right). Biomass on the left are the VAST means and standard errors of the annual estimates of epifaunal biomass (kg). The circles on each map indicate observed biomass and the colors are the density distributions (in kg/km²) of the epibenthos.

Community composition in 2009 and 2010 was very different from other years (Fig. 18). The community in 2018 grouped separate from all other years, trending towards the upper region of the nMDS plot. It should be noted, however, that the only stations sampled in 2018 were located in the southern Chukchi Sea, likely biasing the community composition comparison for this year. Community composition of the remaining years was similar and grouped more closely together. Among the taxa driving this distribution were *Chionoecetes* (snow crab) and *Ophiura* (brittle star), which typically are among the biomass dominant taxa on the shelf, which occurred at much higher biomass in earlier years (Fig. 18).

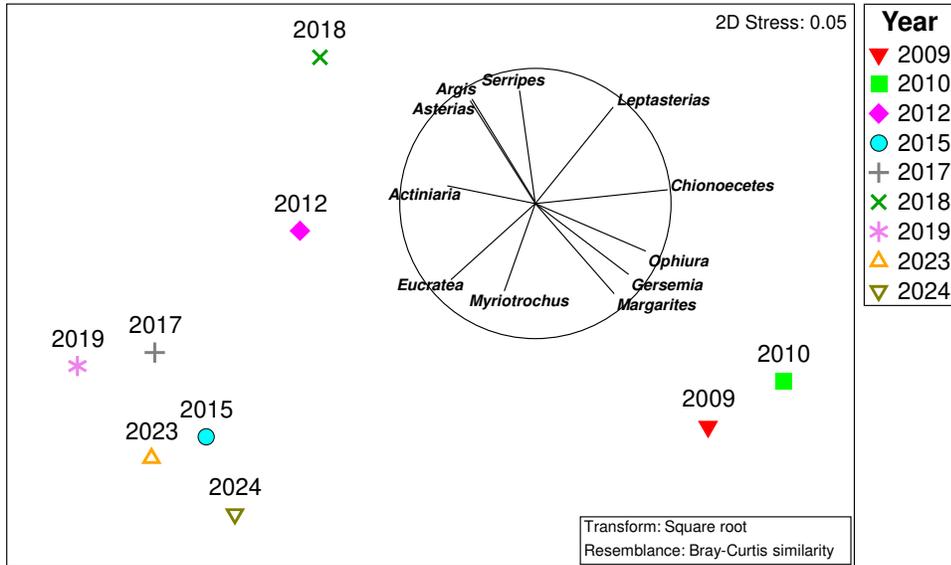


Figure 18. Epibenthic community composition across sampling years in the non-metric multidimensional scaling plot. Vector circle indicates taxa that were driving the distribution of annual community structure, where the individual vector length is relative to the maximum predictor strength (circle size).

Modeled Delta diversity values were variable over time but increased considerably for the last two sampling years in 2023 and 2024 (Fig. 19). Examination of annual spatial distributions suggests that Delta diversity mostly increased in more offshore regions, and this increase was most pronounced in the northern study area in later years.

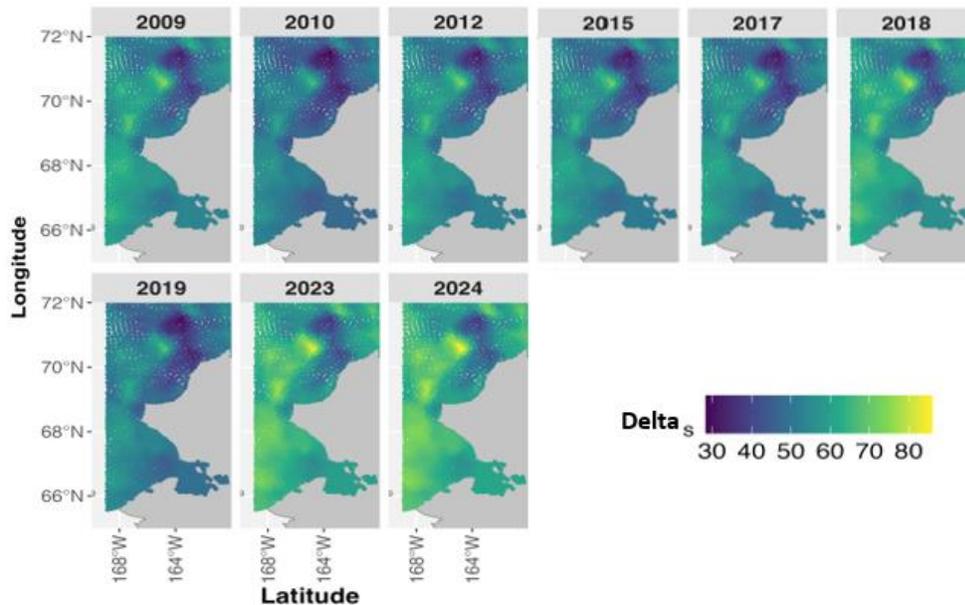


Figure 19. Modeled Delta diversity index for each sampling year. Darker colors refer to lower and lighter colors to higher Delta values.

When considering predicted Delta values per year in relation to latitude, a significant negative trend ($p \leq 0.001$) confirms that Delta diversity overall decreased with increasing latitude (Fig. 20). Overall, however, we did see an increase over time (Fig. 20). When Delta diversity was calculated at repeat stations in the southern (DBO3 line) and northern (DBO4 line) study area, Delta values increased for both sampling lines with sampling year (DBO3 stations: $R^2=0.14$, $F_{(1,17)}=2.7$, $p=0.119$; DBO4: $R^2=0.5$, $F_{(1,10)}=10$, $p=0.01$), but only the increase in diversity over time at the northern DBO4 line was significant.

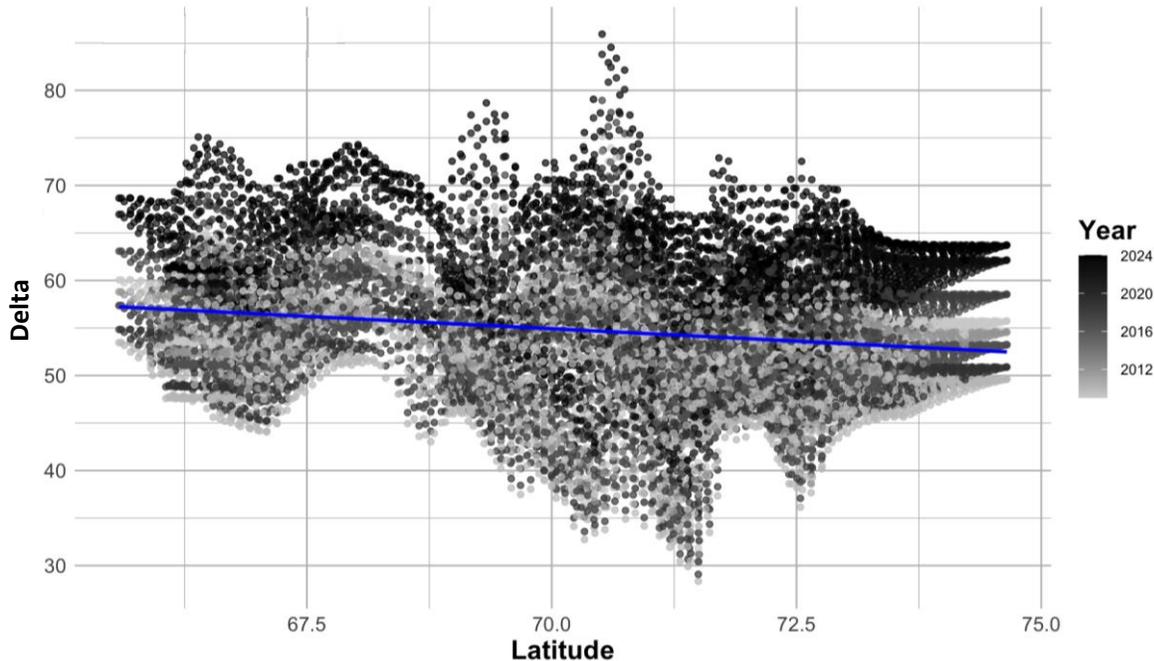


Figure 20. Predicted (VAST model) Delta diversity index for each grid cell for each year, plotted against latitude. Years are indicated in gray scale, with darker shades for later years. The blue line indicates the significant linear regression line over latitude ($p < 0.001$).

3.6.3 Year-round epibenthic imagery

In 2020, AMBON PI Iken submitted a proposal on behalf of the AMBON group to AOOS to obtain instrumentation to add to the CEO that would expand the AMBON observations we already conduct in collaboration with the CEO. We were able to obtain AOOS funding for a benthic camera, which provides time lapse images of the seafloor to observe benthos behavior, movement, density etc. The benthic camera was deployed in 2022 but could not be retrieved in 2023 because of a malfunctioned pop-up float (note: an ROV is planned on being used in 2025 to locate the tripod with the camera). A second camera was deployed in 2023 (cruise SKQ2023-12S) and retrieved in 2024 (cruise SKQ2024-12S). While those cruises are outside this project scope, we mention this here to report the overall success of this endeavor. More than 8,000 images were retrieved, covering most of the year. Below is a small sample of the imagery we were able to obtain (Fig. 21).



Figure 21. Examples of images retrieved from the benthic camera in 2024. Left: The seafloor is densely covered with brittle stars. Middle: A snow crab and a nemertean worm move through the image. Right: A dead jellyfish has sunk to the bottom and provides detrital food for benthic consumers.

3.7 Fish

3.7.1 Essential Fish Habitat

The AMBON project made use of existing data to contribute to the **EOV “Fish abundance and distribution”**. As part of the data synthesis goals of the AMBON project, data on the fish community from two earlier AMBON cruises in 2015 and 2019 were incorporated into a unified database that includes fish catches (catch-per-unit-effort) and available length and weight data from multiple cruises conducted in the Chukchi Sea between 2003 and 2019 (Marsh and Mueter 2023, Fig. 22). This work was a data rescue project conducted funded by AOOS with additional support by the AMBON project, with the goal of making the data available via the AOOS Arctic Portal.

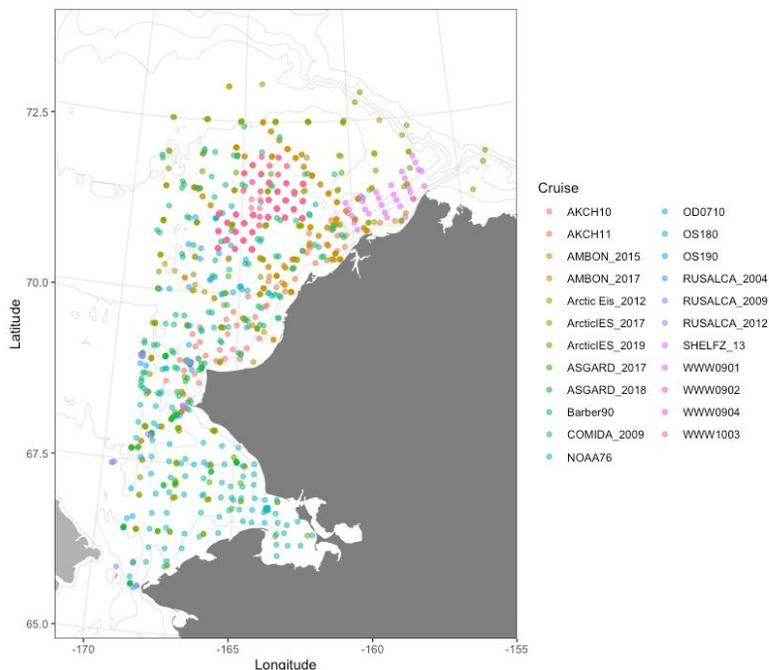


Figure 22. Haul locations for all stations sampled by bottom trawl or Issac-Kidds Midwater Trawl (IKMT) in the US portion of the Chukchi Sea between 1990 and 2019 by cruise. Data from these cruises were included in the database.

These data were then also included in a comprehensive report presented to the North Pacific Fisheries Management Council on Essential Fish Habitat (EFH) of Arctic cod, saffron cod and snow crab in the

Chukchi and Beaufort seas (Marsh et al. 2023). This work, funded by BOEM with partial support by the AMBON project, provides an important update for the Arctic Fisheries Management Plan. The data included important fish capture data obtained from the AMBON 2015 and 2017 cruises, providing much environmental context as these two years differed greatly in ocean temperatures (for a comparison of the two years also see Mueter et al. 2021a).

Abstract of report: *Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area*; Marsh et al. 2023

The Arctic Fishery Management Plan (FMP) includes three target species, Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*), for consideration of potential future commercial fishing activities in the Arctic Management Area that encompasses the U.S. Chukchi and Beaufort Seas. Arctic species EFH descriptions and maps are not currently informed by species distribution models (SDMs) as has been the approach for the groundfish and crab FMPs in the 2017 and 2023 EFH 5-year Reviews. Our study uses environmental and biological survey data from 2000–2018 and SDMs to advance EFH descriptions and maps for Arctic species' life stages current with the state of science for the region. A total of 13 EFH Level 1 maps (distribution) and three EFH Level 3 maps (habitat-related vital rates) are available for these three species and up to four life stages for the Arctic FMP in the 2023 Review. The Arctic climate and oceans are rapidly warming and will likely have far reaching impacts on marine ecosystems, including fish and crabs. We also compare the probability of suitable habitat distribution and area occupied in warm and cold years as a first step to consider climate change effects on EFH for Arctic species.

3.7.2 Fish functional diversity

The Arctic marine system is characterized by dramatic seasonal and interannual swings in environmental conditions such as available light, water temperature, and ice cover (Danielson et al. 2020). The Arctic, and specifically the Chukchi Sea, has seen a long-term shift in environmental conditions, with increased summer temperatures, less sea ice cover, and increased advection through the Bering Strait (Clement Kinney et al. 2014, Danielson et al. 2020, Zhang et al. 2024). Additional environmental changes are on the horizon, including further declines in sea ice cover and an increasing influx in sub-Arctic species into Arctic waters during a portion of the year. (Axler et al. 2023, Levine et al. 2023, Husson et al. 2024). Boreal species that may be beginning to establish themselves in Arctic regions can disrupt ecosystem processes through everything from competitive interactions to shifts in energy flow through the food web (Mueter and Litzow 2008, Møller and Nielsen 2020, Alabia et al. 2023). For example, an increase in species like walleye pollock and Pacific cod could exert greater predation pressure on other demersal fish species and the benthic community than is currently observed (Wildes et al. 2022, Orlov and Volvenko 2024). Given these changes, we examined the functional traits that characterize demersal fish communities of the Chukchi Sea and linked these traits to environmental drivers, in order to develop a more holistic understanding of the drivers and the functioning of fish communities in the Chukchi Sea.

Data on fish community that had been compiled by Marsh and Mueter (2023) from research surveys conducted during the open water seasons in the Chukchi Sea between 2007 and 2019 using a plumb-staff beam trawl. Fishing effort for each haul was defined as the total seafloor area swept by the net and standardized to an area of 1,000 m² as catch per unit effort (CPUE). Fish functional composition was quantified using a combination of six biological traits that describe the taxa's behavior, life history, and morphology (Beukhof et al. 2019). Each trait was categorized by 3-6 modalities, which are specific categories within each trait. We used various ordination techniques, specifically community-weighted mean redundancy analysis (CWM-RDA), to identify groupings of fish assemblages based on these traits and relate them to environmental conditions (Dolédec and Chessel 1994). Environmental variables included in the analysis were bottom temperature, bottom salinity, and ice retreat date (from satellite imagery). In addition, we included latitude, longitude and depth to account for any remaining spatial

patterns and depth gradients, as well as year to account for remaining interannual variability. To further examine spatial gradients in trait and species compositions we conducted cluster analyses of stations based on trait profiles (functional clusters) and compared those to taxonomic clusters based on species compositions.

The three functional composition clusters were spatially distinct with considerable overlap, defining a south to north gradient with a southern cluster (red), a predominantly northern cluster (blue), and an intermediate cluster (green) (Fig. 23). All functional clusters predominately contained taxa with medium age at maturity and medium body size. Additionally, the southern functional cluster was dominated by very high longevity, and both the southern and northern clusters were dominated by medium fecundity and eel-like body shapes. The intermediate functional cluster was dominated by medium/high and high fecundity and fusiform body shape. There was visual evidence that the spatial extent of the three clusters varied among years with fewer northern cluster sites present in more recent years (Fig. 23).

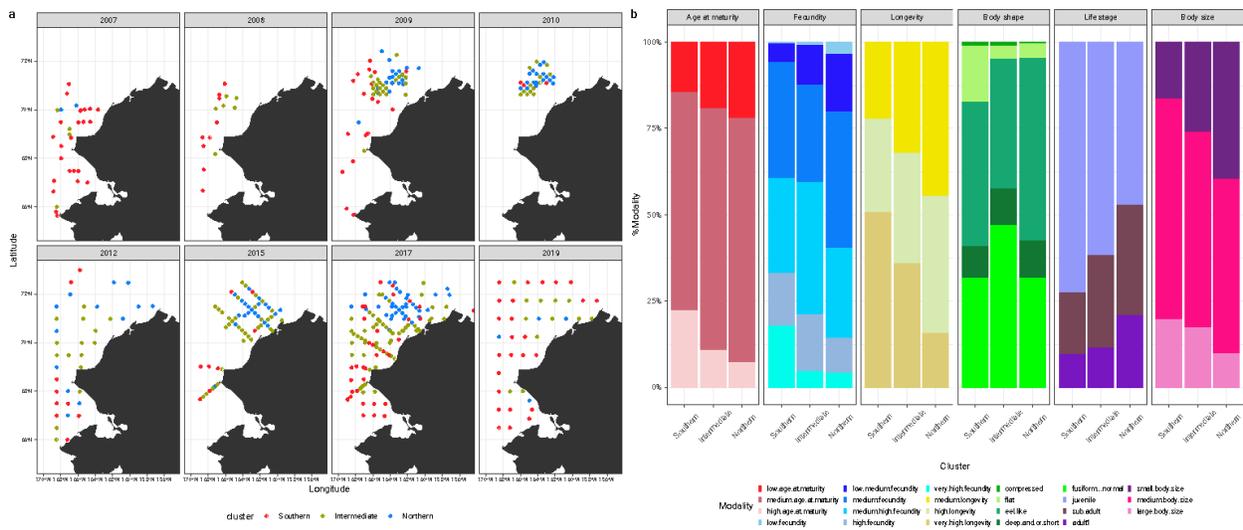


Figure 23. Fish taxonomic trait cluster distribution and functional composition of three major fish assemblage clusters in the Chukchi Sea. Maps show the annual distribution of the three clusters across the Chukchi Sea.

The best model with all environmental variables and spatio-temporal gradients (latitude, longitude, year) explained 21.3% of the total variation in functional community composition across sites (Fig. 24). Functional composition changed primarily along a gradient from low to high temperatures, late to early ice retreat, and offshore to onshore gradients. A secondary gradient was associated with increasing latitude and longitude from the southwest to the northeast. Specific modalities that drove differences across fish community composition were generally associated with specific environmental gradients. Very high longevity and juvenile life stages were associated with higher temperatures, earlier ice retreat, and proximity to shore. Small body size and mid-adult life stage were associated with lower temperatures and later ice retreat, while the prevalence of medium and high longevity tended to increase towards the northeast (higher latitudes and more western longitudes) (Fig. 24).

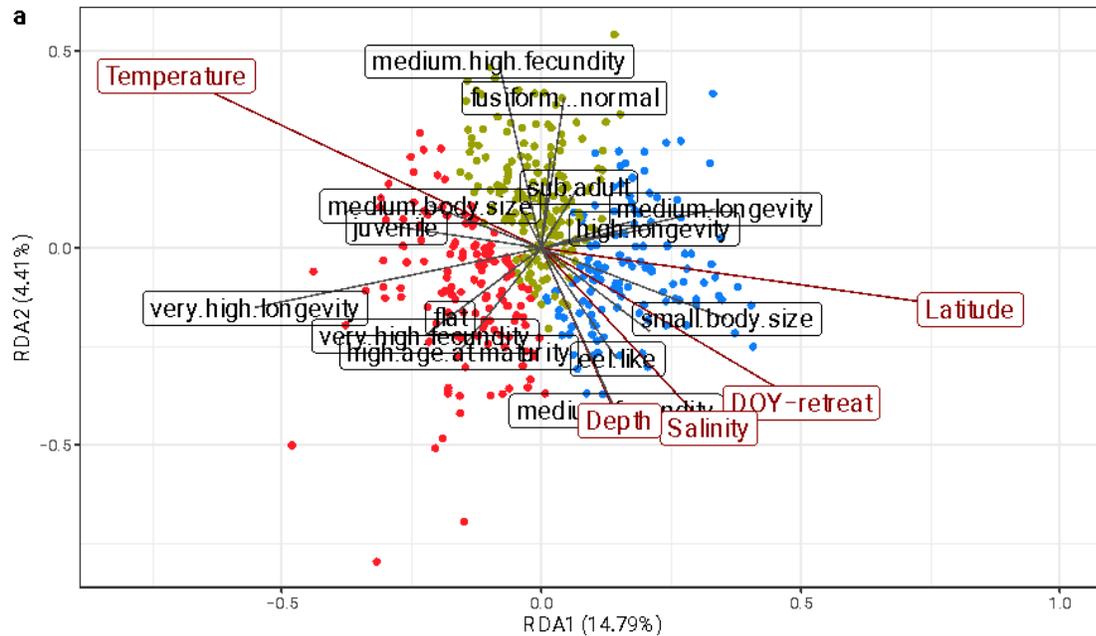


Figure 24. Community-weighted mean redundancy analysis (CWM-RDA) that ordinales the clusters (colored dots) with specific traits (black font boxes) and to environmental conditions (red font boxes).

This work is in advanced stages of manuscript preparation to be submitted soon to a peer-reviewed journal (TBD): Sutton L, Forster CE, Iken K, Mueter FJ. *The role of static and dynamic environmental drivers in shaping Arctic fish functional diversity.*

3.8 Seabirds

In alignment with NOAA/IOOS' efforts to enhance the AMBON program's focus on animal tracking science, we collaborated with colleagues in Australia who track short-tailed shearwaters (*Ardenna tenuirostris*) (as part of the **EOV "Birds"**). These birds undertake extensive annual migrations between their breeding grounds in the Southern Hemisphere and non-breeding foraging areas in the Northern Hemisphere. Short-tailed shearwaters (hereafter referred to as shearwaters) are among the most abundant seabird species in both the AMBON study region and the Bering Sea during summer and early fall (Kuletz et al. 2015, Gall et al. 2017). Their wide distribution, abundance, and fairly omnivorous diet make them valuable indicators of ecosystem change.

Shearwaters forage both at the water's surface and by diving to depths of up to 70 meters to capture deeper prey. Because they are not tied to colonies while in the Northern Hemisphere, they can track prey over vast distances. Their diet consists primarily of fish larvae, small fish, cephalopods, and small crustaceans, particularly euphausiids (Hunt et al. 2002, Nishizawa et al. 2017). As opportunistic foragers, their diet reflects the abundance and composition of lower trophic level in the marine ecosystem. This study employed bulk stable isotope analysis (SIA) of carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$) and oxygen ($\delta^{18}\text{O}$) in shearwater feathers combined with light sensitive geolocator to infer foraging locations. The primary objectives were (1) to identify major Northern Hemisphere foraging sites, and (2) to investigate how foraging patterns align with diet (trophic level), as reflected in newly grown feathers during the shearwater's occupation of the Southern (breeding) and Northern (non-breeding) hemispheres. Beyond serving as ecosystem indicators in the AMBON study area, insights from these foraging patterns may

have implications for shearwater breeding populations in Australia. A better understanding of the spatio-temporal trophic patterns of this key species will contribute to a broader knowledge of trophic linkages within the Arctic ecosystem.

Feather samples were collected by Australian colleagues Duncan Sutherland (Phillip Island Nature Parks, Victoria, Australia) and David Boyle (Victorian Ornithological Research Group) from shearwater breeding colonies in southern Australia under their national permits. We prioritized SIA of feather samples from birds with available tracking data, provided by Dr. Boyle and Dr. Sutherland, which will be archived in Movebank. Stable isotopes were analyzed at the Western Australia Biogeochemistry Center at the University of Western Australia.

Feather samples were obtained from live birds caught at their nest burrows, with breast (body) feathers – grown in the Southern Hemisphere – and wing feathers – grown in the Northern Hemisphere – selected for analysis. Using tracking data to confirm foraging locations, we then analyzed bulk isotopic patterns across sampled individuals to explore trophic interactions in different areas at the time of feather growth. This dataset represents a single foraging year in the Northern Hemisphere, spanning 2021–2022. Feather samples (specifically the 3rd secondary covert from the wing elbow) were analyzed for 26 individuals (both breast and wing feathers), with an additional 11 individuals analyzed exclusively for breast feathers.

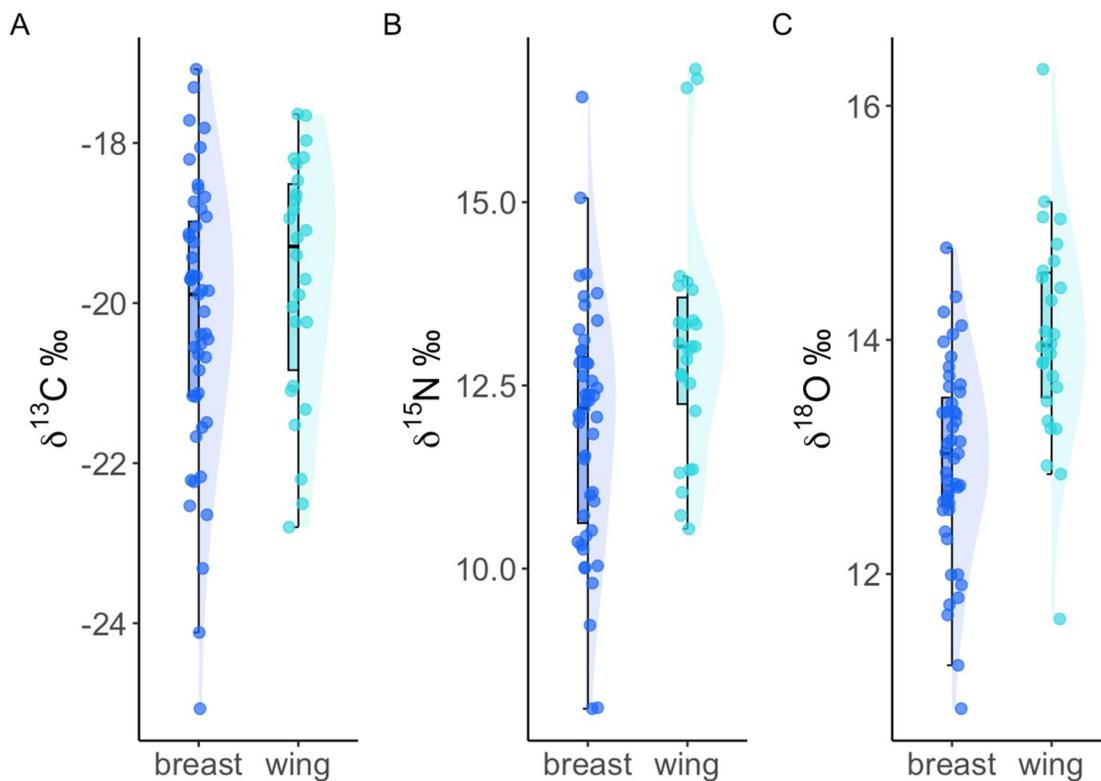


Figure 25. Violin plot showing the range and distribution of stable isotope ratios of A) carbon ($\delta^{13}\text{C}$), B) nitrogen ($\delta^{15}\text{N}$), and C) oxygen ($\delta^{18}\text{O}$) in the breast and wing feathers of short-tailed shearwaters.

Table 1. Stable isotope ratios (mean \pm standard deviation) for breast and wing feathers of short-tailed shearwaters.

Feather Type	$\delta^{13}\text{C}$ (Mean \pm SD)	$\delta^{15}\text{N}$ (Mean \pm SD)	$\delta^{18}\text{O}$ (Mean \pm SD)
Breast	-20.21 \pm 1.75	11.92 \pm 1.67	12.97 \pm 0.83
Wing	-19.68 \pm 1.52	13.09 \pm 1.66	14.02 \pm 0.92

The lower $\delta^{13}\text{C}$ values in the Southern Hemisphere (breast feathers, Fig. 25, Table 1) likely indicate that shearwaters are feeding in waters with more phytoplankton or surface primary producers (which tend to have lower $\delta^{13}\text{C}$ values). In the Northern Hemisphere, the slightly less negative $\delta^{13}\text{C}$ suggests that the shearwaters may be feeding in waters with different primary production, potentially more dependent on upwelling or deeper oceanic food webs, which tend to be slightly enriched in carbon (^{13}C). This could reflect different marine environments and primary production sources between the Southern and Northern Hemispheres. The higher $\delta^{15}\text{N}$ values in the Northern Hemisphere (Fig. 25, Table 1) still suggest that shearwaters are feeding at a higher trophic level in Alaska, as their diet likely shifts to include more higher-level consumers in those colder northern waters. In contrast, the slightly lower $\delta^{15}\text{N}$ values in the Southern Hemisphere could indicate a diet with a slightly lower trophic level in the waters of the Southern Hemisphere, possibly feeding on smaller fish, crustaceans, or other invertebrates. The higher $\delta^{18}\text{O}$ values in the Northern Hemisphere indicate that the shearwaters are likely feeding in colder waters in Alaska. In the Southern Hemisphere, the lower $\delta^{18}\text{O}$ values suggest feeding in relatively warmer waters, consistent with environments around southern Australia or the Southern Ocean.

Next, we used the R-package *NicheROVER* to model the isotopic niches corresponding to the periods represented by each feather type, with these niches serving as proxies for trophic niches (Fig. 26). This analysis allowed us to quantify niche size and the degree of overlap between breast and wing feathers. The estimated niche sizes were 130.20 for breast feathers and 146.19 for the wing feathers, suggesting a broader isotopic niche for shearwaters foraging in the Northern Hemisphere (Fig. 26). However, without isotopic data from prey sources, it remains uncertain whether this broader niche reflects greater dietary diversity, a wider range of habitat use, or simply the consumption of fewer prey items with more divergent isotopic values, rather than a truly expanded prey base.

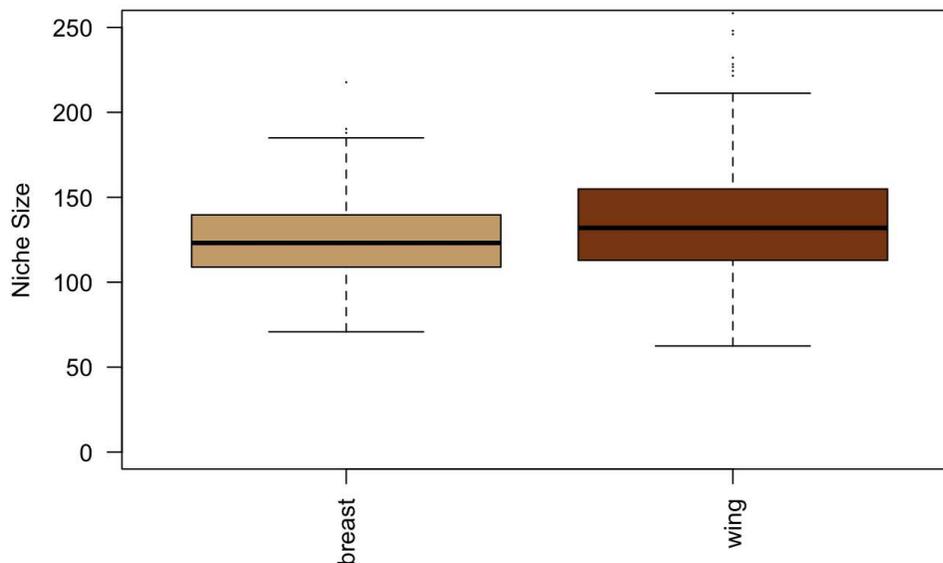


Figure 26. Isotopic niche size for breast and wing feathers of short-tail shearwaters, indicating a larger niche size for wing feathers.

The results also showed notable overlap in the isotopic niches of breast and wing feathers (75.29%, CI: 70.04–88.64%), suggesting shared food resources (potentially same zooplankton or fish species or in the same trophic level) between the two foraging periods (Fig. 27).

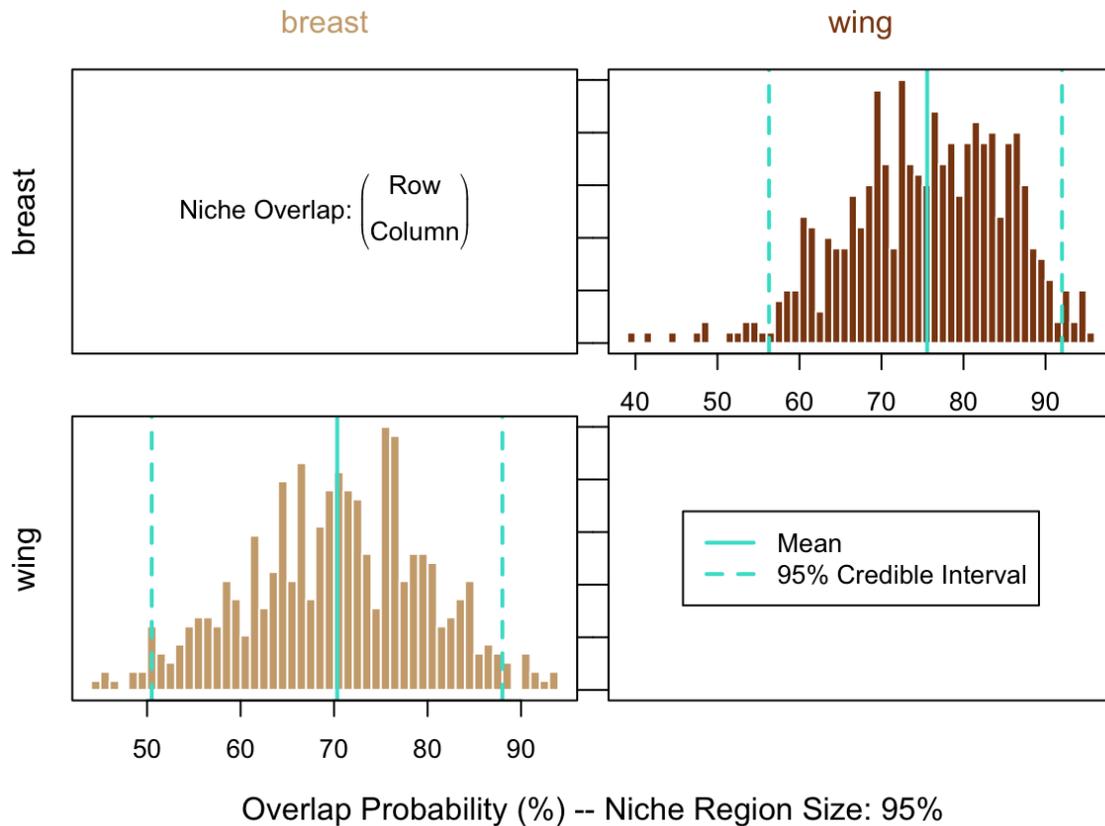


Figure 27. Posterior distribution of the probabilistic niche overlap (%) within a 95% isotopic niche region for breast and wing feathers of short-tailed shearwaters. Solid turquoise lines represent the posterior means, while dashed turquoise lines indicate the 95% credible intervals.

Using tracking data provided by our Australian colleagues Boyle and Sutherland, we examined whether distinct isotopic patterns corresponded to different foraging locations (Fig. 28, Table 2) and we discuss how these areas relate to the observed isotopic values. Notably, none of the tagged shearwaters traveled into the Chukchi Sea, suggesting that breeding birds (from which our feather samples were collected) may not frequent this northernmost migration route as often as younger, non-breeding birds. For the Eastern Aleutians, high $\delta^{13}\text{C}$ (mean = -18.4) and particularly $\delta^{15}\text{N}$ (mean = 16.7) values (Fig. 29) indicate a reliance on prey from higher trophic levels such as fish larvae and use of more coastal or productive waters. The Western Aleutians group, on the other hand, showed lower $\delta^{13}\text{C}$ (mean = -21.4) and $\delta^{15}\text{N}$ (mean = 11.0) values (Fig. 29), indicative of more pelagic feeding habits and reliance on lower trophic-level prey, such as zooplankton and euphausiids. The Central Aleutians group displayed intermediate $\delta^{13}\text{C}$ (mean = -18.9) and $\delta^{15}\text{N}$ (mean = 12.6) values (Fig. 29), suggesting a more balanced diet that includes a combination of pelagic and coastal prey. This suggests that the Central Aleutians might serve as a transition zone, where shearwaters can access both lower trophic-level prey as well as higher trophic-level species in coastal waters, mirroring the mixed environmental conditions of the area. The Northeast Japan group exhibited intermediate $\delta^{13}\text{C}$ (mean = -19.1) and $\delta^{15}\text{N}$ (mean = 13.3) values (Fig. 29), indicating a mix of pelagic and coastal feeding habitats. These intermediate values likely reflect a diet that includes both lower trophic-level prey (such as small fish and invertebrates) and slightly higher trophic-level

species found in the coastal waters. The birds in Japanese foraging regions had distinct $\delta^{18}\text{O}$ values when compared to the other foraging locations, suggesting environmental or water mass influences different from the Aleutian regions (Fig. 29). These values likely reflect differences in the water sources encountered during foraging, which may be associated with specific oceanographic conditions, such as water temperature, salinity, or the mixing of distinct water masses. Across the foraging regions and using all isotope data combined, short-tailed shearwaters had the most unique diet in the Eastern Aleutians (Fig. 30).

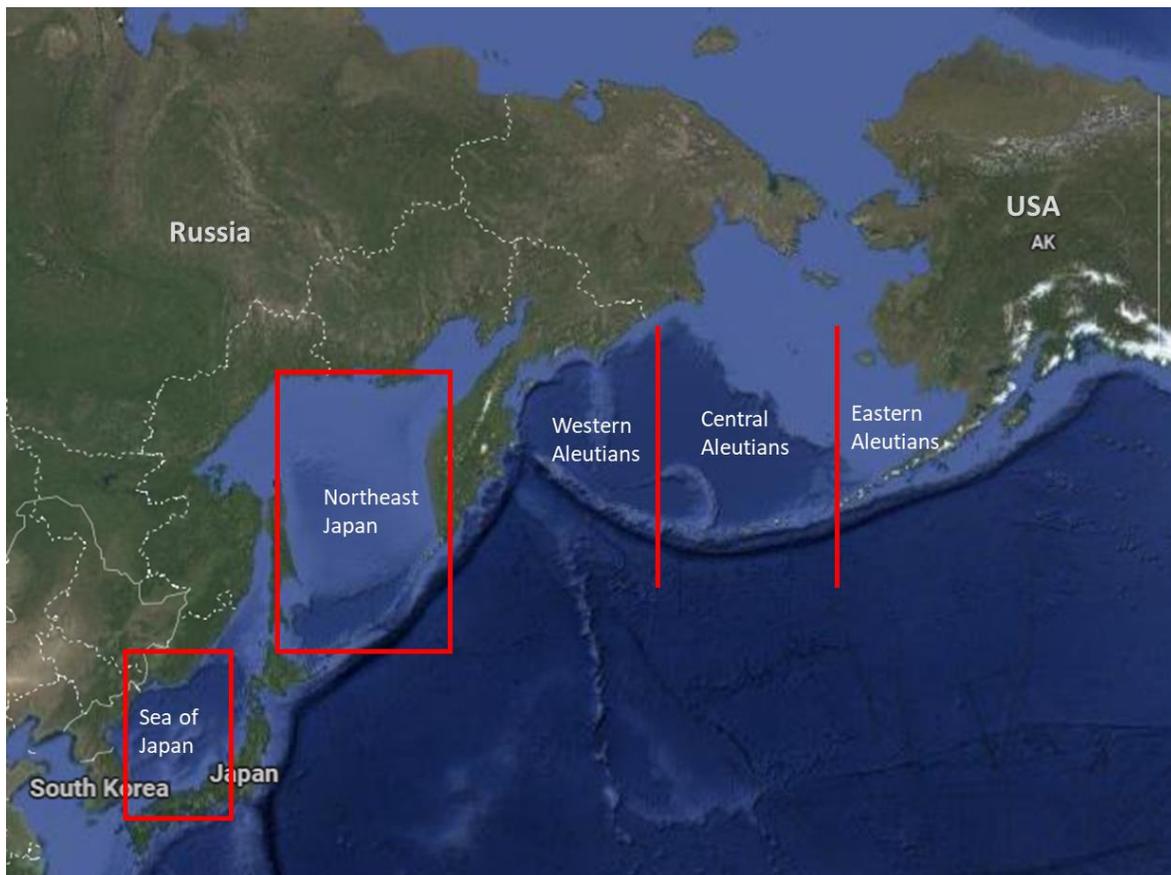


Figure 28. Foraging areas delineated based on regions where geolocator-tagged short-tailed shearwaters foraged.

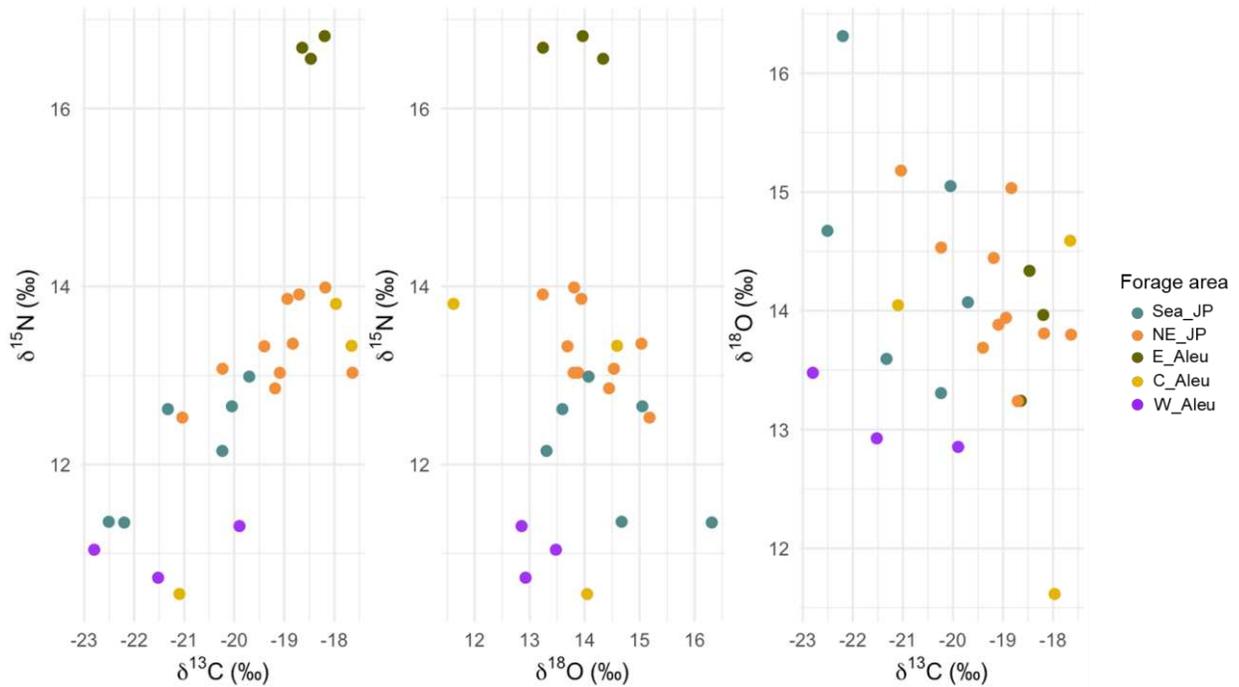


Figure 29. Range and distribution of stable isotope ratios of carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$), and oxygen ($\delta^{18}\text{O}$) in short-tailed shearwaters.

Table 2. Stable isotope ratios (mean \pm standard deviation) for short-tailed shearwater wing feathers in different foraging areas, based on geolocator tracking data.

Forage Area	$\delta^{13}\text{C}$ (Mean \pm SD)	$\delta^{15}\text{N}$ (Mean \pm SD)	$\delta^{18}\text{O}$ (Mean \pm SD)
Eastern Aleutians	-18.4 ± 0.2	16.7 ± 0.1	13.8 ± 0.5
Central Aleutians	-18.9 ± 1.9	12.6 ± 1.7	13.4 ± 1.5
Western Aleutians	-21.4 ± 1.4	11.0 ± 0.2	13.1 ± 0.3
Northeast Japan	-19.1 ± 0.9	13.3 ± 0.4	14.2 ± 0.6
Sea of Japan	-21.0 ± 1.1	12.2 ± 0.6	14.5 ± 1.1

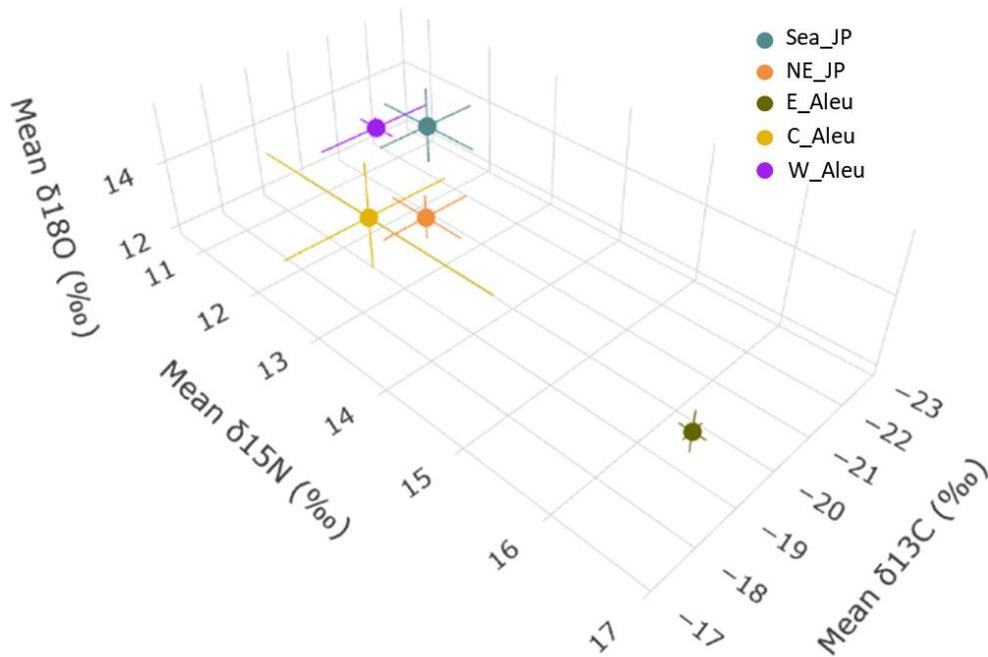


Figure 30. Mean stable isotope values ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$) of short-tailed shearwaters (wing feathers), grouped by summer foraging region, as determined from geolocator tracking data. The colors represent different foraging regions.

3.9 Marine Mammals

The biological impacts of climate changes in the Arctic range from invasions from subarctic species, changes in phenology of Arctic species, and changes in Arctic food webs. The added pressure of increased economic ventures highlights the urgent need for long-term observations in the Arctic Ocean, including changes in biodiversity. Marine mammal sound has been recorded using a passive acoustic recorder since 2015 at the CEO site, where the thriving benthic community provides a major walrus feeding ground (Jay et al. 2012, Grebmeier et al. 2015). From 2019-2021, the passive acoustic recorder on the CEO has been supported by this AMBON project to monitor the presence of vocal marine mammals and the overall **EOV of “Sound”** as well as **“Marine mammals”**.

The hydrophone package was programmed to record acoustic data from 10 Hz to 8 kHz on a 25% duty cycle (the first 15 min of every hour) for the duration of each year’s deployment. Upon recovery, the data were visually and aurally examined to determine the presence/absence of pinniped (walrus and bearded seal) and cetacean (bowhead and beluga whale) vocalizations (Fig. 31).

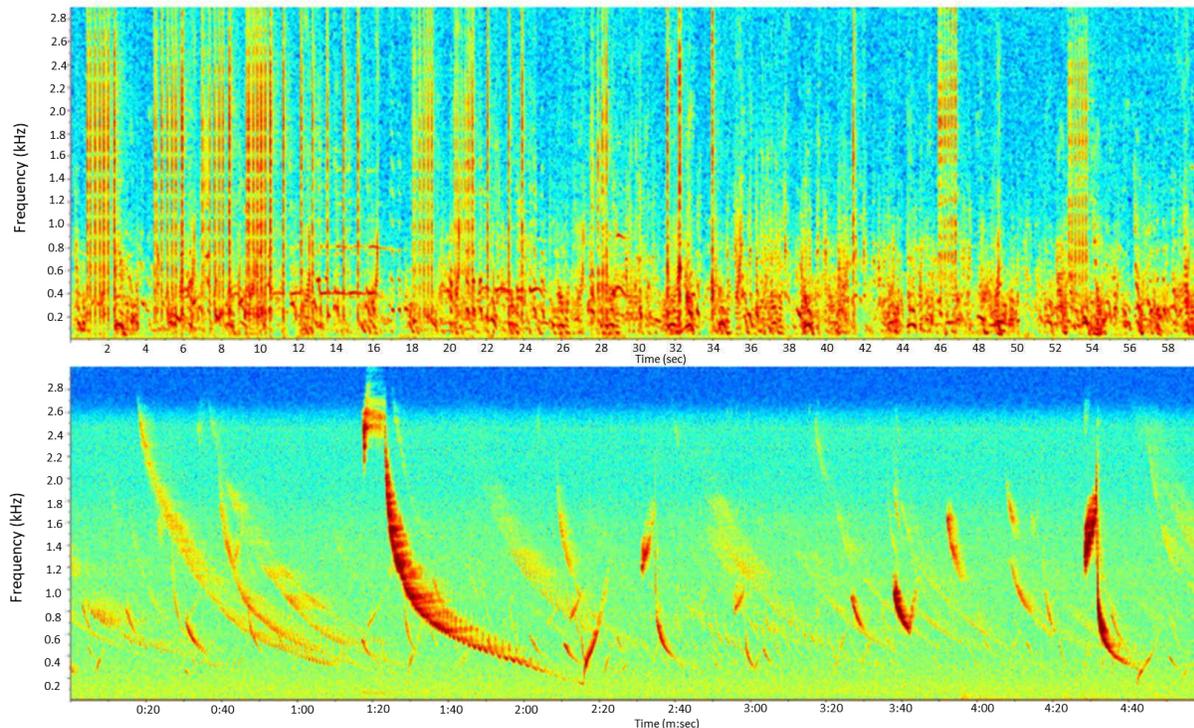


Figure 31. Spectrograms of characteristic signals produced by walrus (top panel) and bearded seals (bottom panel) used to detect the presence of each species. Note the different time axes.

3.9.1 Pinnipeds – walrus and bearded seals

Each of these species (walrus and bearded seals) contribute significantly to the overall underwater soundscape at the CEO region but at different times of the year (Fig. 32). Walrus sounds typically start in late May, when sea ice concentration begins to abruptly decrease and can be heard continuously until early November annually. Walrus vocalizations cease 1-3 weeks before sea ice begins to form in the fall. In contrast, bearded seals are only seldom heard during the open water period, but their vocalizations are recorded 24 h per day as soon as sea ice concentrations increase to over ~75% in early December. The presence of walrus at the CEO site is consistent from year to year; this species was heard from May until late October annually and likely reflects the migratory phenology of Pacific walrus (Fig. 32). However, the high number of hours with detections in October in the study period is somewhat inconsistent with earlier data and with other acoustic detections reported by other investigators (Hannay et al. 2013). This is a clear indication that walrus have changed their haul-out behavior in the Chukchi Sea as the decline of sea ice has resulted in thousands of animals on shore of northwestern Alaska (Udevitz et al. 2012, Johnson et al. 2024).

Bearded seal trills can be heard throughout the winter into late June/early July and decline with declining sea ice concentration. An exception was in 2019, when there was little or no ice at the CEO from late May to mid-June, but bearded seals were nevertheless recorded at very high levels. Bearded seals appear to be year-round residents of the Chukchi Sea; however, they are only vocally active seasonally (Fig. 32). Males produce elaborate trills (see Fig. 31) to attract females and for male-male interactions. Bearded seal trill production is closely linked to their breeding season and the presence of sea ice, on which they haul out, give birth, and nurse young. During the open water season, bearded seals are present in the Chukchi Sea but produce many fewer sounds.

Although both walrus and bearded seals are Arctic endemic species that rely on sea ice for critical life history stages, and fill similar ecological niches, they clearly have different timing in their occupation of the CEO region. This suggests that these Arctic pinnipeds may be partitioning this region of the Arctic based on the presence or absence of sea ice, reducing overall competition between the two species.

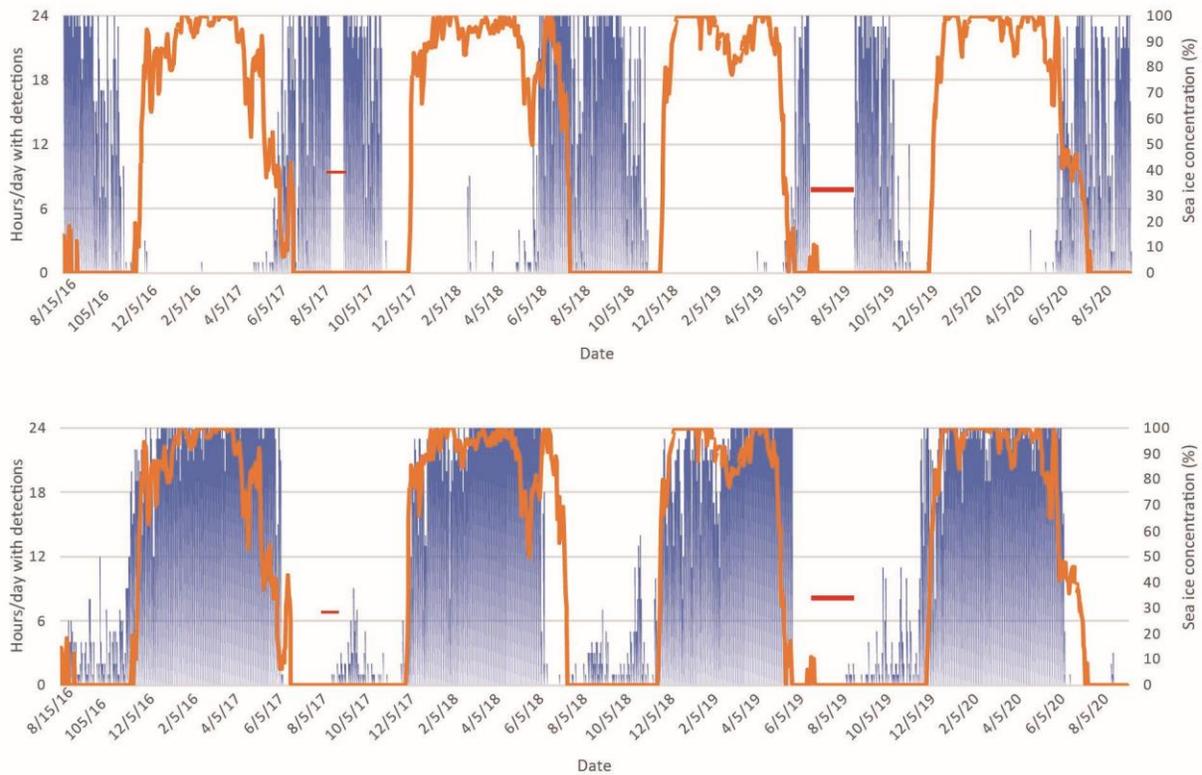


Figure 32. Acoustic detections of walrus (top panel) and bearded seals (bottom panel) with sea ice concentration (orange line) at the Chukchi Ecosystem Observatory from 2015-2020, since 2019 as part of the AMBON program. The orange line represents sea ice cover, the blue peaks indicate vocalizations. Red stars and arrows indicate missing data.

3.9.2 Cetaceans – bowhead and beluga whales

Bowhead whales were recorded, in general, during two main periods of each year, once on their northbound spring migration and once on their southbound fall migration (Fig. 33). During the fall migration, they were heard in relatively heavy ice concentrations and acoustic detections occurred in bouts rather than continuously, unlike during the spring migration when bowheads were recorded daily. Relatively fewer hours per day with bowhead signals occurred during the spring, likely because the population tends to migrate closer to the coast of Alaska where seasonal spring flaw leads open and permit them to migrate towards feeding grounds in the Canadian Beaufort Sea. Of note is that more bowhead whales are being detected during winter times with less ice cover, supporting other data suggesting that this population may be shifting its wintering range northwards as sea ice continues to thin and retreat (e.g., Citta et al. 2023, Szesciorka et al. 2024). A shift in species populations is also discernible from an increasing occurrence of killer whales in the study region in later years as sea ice is thinning and less abundant (data not shown).

Beluga whales were recorded most often annually beginning in April and into June but more infrequently in the fall (Fig. 33). This timing suggests they could be from either the Beaufort Sea or eastern Chukchi stock of belugas. In fall months, they were only recorded when sea ice concentrations were low. Because beluga whales produce high frequency calls, we assume their presence from 2016-2019 was likely underestimated as the instruments used only listened up to 8 kHz and because high frequency signals do not propagate as far as lower frequency signals.

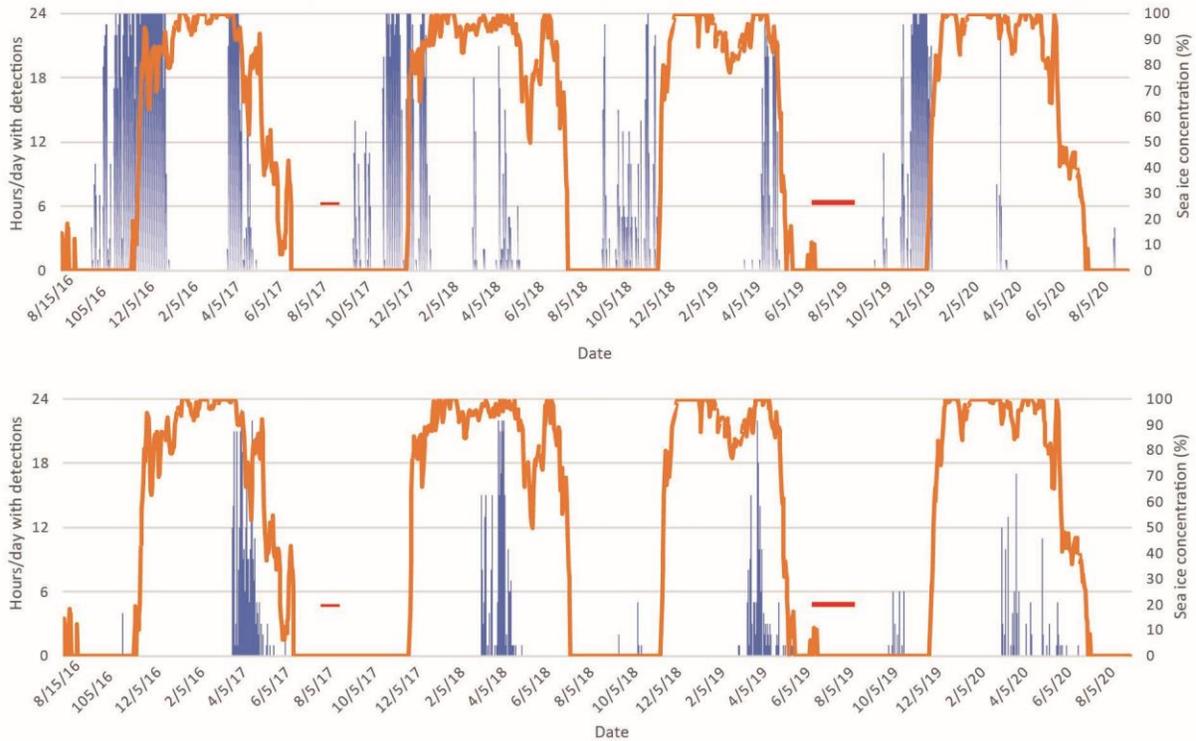


Figure 33. Acoustic detections by day in comparison to sea ice concentration (orange line) are shown for bowhead whales (top panel) and belugas (bottom panel) at the Chukchi Ecosystem Observatory from 2015-2020. Red stars indicate missing data.

3.9.3 Soundscapes

To understand the varying underwater soundscape at the Chukchi Ecosystem Observatory, year-long long-term spectral averages (LTSA) were generated for each hydrophone deployment. These LTSAs show seasonal and interannual variation due to the presence of sea ice, storms and marine mammal vocalizations. Ambient noise levels are lowest when sea ice cover is most extensive, and storm events can be seen as short-term increases in ambient noise. Likewise, the vocalizations of bowhead whales and bearded seals, for example, show distinct patterns in the LTSAs. LTSAs from 2017-2020 and 2021-2022 (the hydrophone failed in 2020-2021) are shown below with example signals highlighted on different LTSAs (Fig. 34).

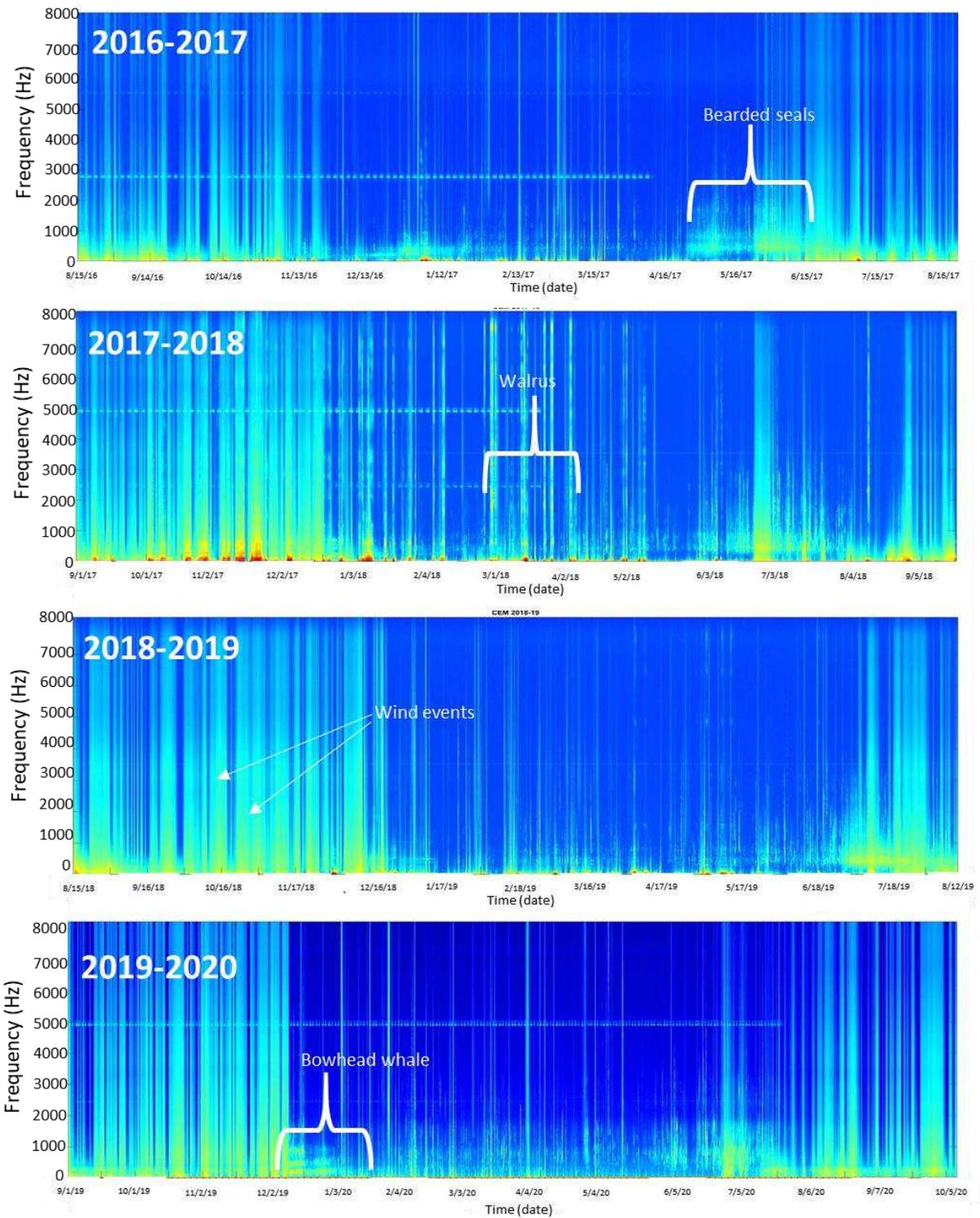


Figure 34. Annual long-term spectral average for 2016-2020 from the passive acoustic recorder at the Chukchi Ecosystem Observatory, as part of the AMBON project. The 'dots' around 3 kHz and 5 kHz are artefacts from the co-located ADCP on the moorings. Example signals are indicated.

3.10 Seascapes

Seascapes are classified and used as a biogeographical framework to describe dynamic, changing ocean habitats with parameters derived from dynamic fields of satellite and modelled data (Kavanaugh et al. 2016). It is a concept applied globally but that can be refined at greater resolution for specific regions, although sea ice cover and high seasonality, as well as limited usable satellite data available from the region make seascape applications in the Arctic challenging. Seascapes provide information about the quality and extent of different oceanographic habitats or features. Current global seascape products include monthly and 8-day time steps at 5 km resolution. They use remotely sensed chlorophyll-a, chromophoric dissolved organic matter, normalized fluorescent line height, sea surface temperature, AVISO sea surface height, microwave sea-ice concentrations, and ECCO2 salinity data (Kavanaugh et al. 2014). Objective classification and validation of remotely-sensed dynamic seascapes using high resolution (1 km) satellite data has occurred at regional to local scales in temperate-upwelling and tropical reef environments. Global seascapes products are available on NOAA CoastWatch (<https://coastwatch.noaa.gov/cwn/product-families/seascape-classification.html>). Seascapes provide a framework to assess and scale up patterns of biodiversity and effects of environmental change on pelagic community structure, ranging from microbes to fish.

In this AMBON project, with additional funding obtained by AMBON PIs Iken and Kavanaugh from AOOS, we were able to add additional understanding of the seascape concept in the Arctic, which turns out to be a challenging region to apply the standard seascape classifications because of the high seasonality and long sea ice cover. The goal of this work was to increase the accessibility and application of a regionally downscaled seascape product for the U.S. Arctic region. We first developed separate seascape analyses for the southern and the northern Chukchi Sea, based on our understanding from our previous AMBON-related work that the two parts of the Chukchi Sea function and respond very differently physically and biologically. We saw greater prominence of seascapes 12, 14 and also 19 (subpolar, temperate upwelling, Arctic subpolar shelves, respectively, Fig. 35) in the southern compared with the northern region. Seascape 33 (pack ice) developed in both regions but extended over longer times per year in the north. This is consistent with the typically earlier ice retreat in the southern Chukchi Sea. In both regions, this seascape diminished over the years (Fig. 35), which reflects the overall decline in Arctic sea ice cover. Interestingly, the diminishing sea ice cover resulted in larger ice-edge phytoplankton blooms in the north, but not in the south (Fig. 36). Possibly, the sea ice in the south has reached a threshold of positive effects on primary production.

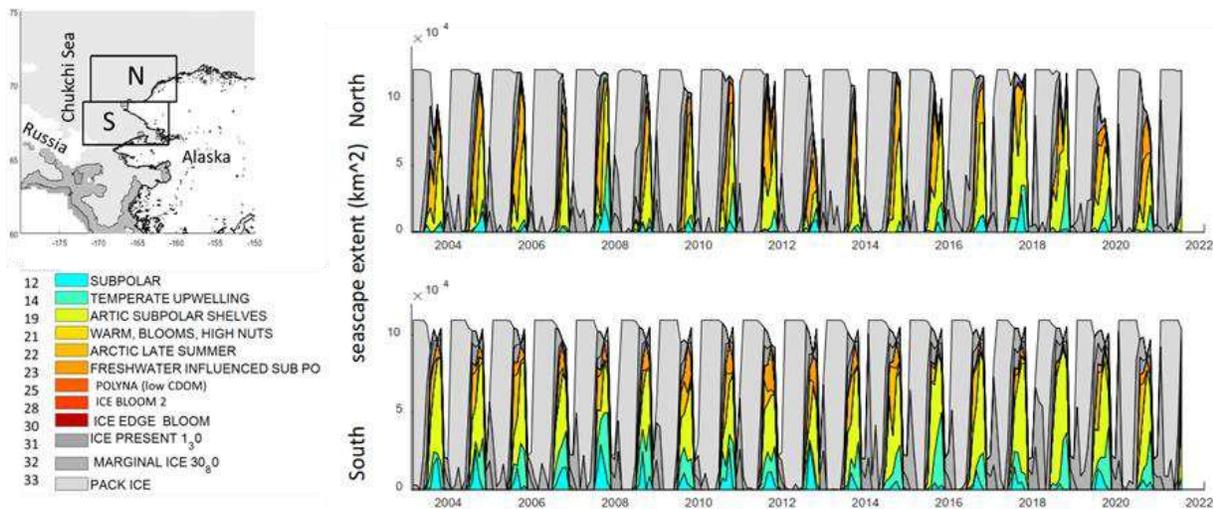


Figure 35. Seascape classifications separately for the northern (top panel) and southern (bottom panel) Chukchi Sea between 2003 and 2021.

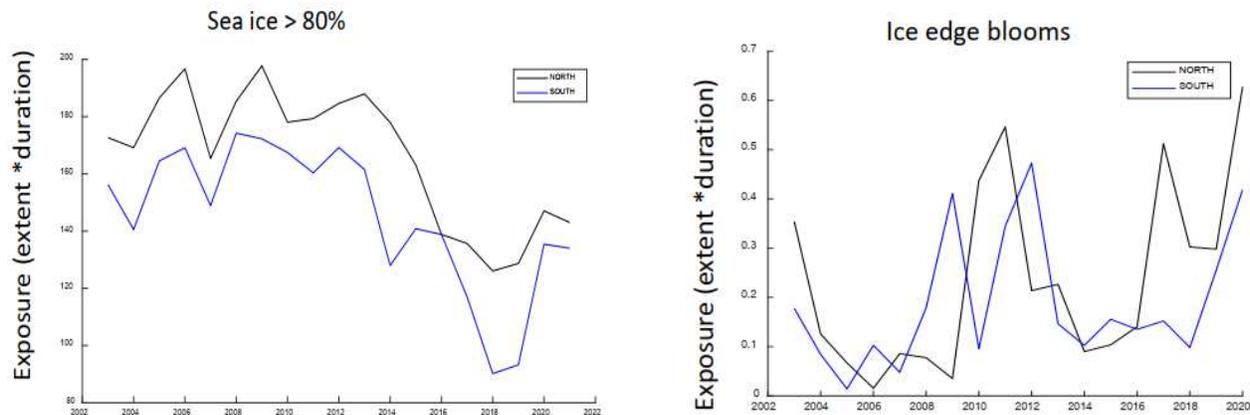


Figure 36. Sea ice cover (left panel) and ice edge blooms (right panel) in the northern and southern Chukchi Sea. The decrease in sea ice cover in the north is associated with an increase in ice edge blooms, but less in the south.

We then added a polar ecosystem case study to demonstrate transferability and to track changes in multi-trophic level diversity in response to changing sea-ice, temperature and nutrient delivery, and ocean chemistry in the Arctic. An important difference to the global model is that the downscaled model uses regionally modeled data for sea surface temperature, salinity, sea surface height, sea-ice concentration from (Pan-Arctic Regional Ocean Model) PAROMS models. PAROMS is a three-dimensional, temporally explicit framework for modeling ocean circulation where many environmental variables, including bottom temperature and bottom salinity, have been modelled dating back to the 1980s.

The initial steps included:

- accessing appropriate PAROMS model runs;
- interpolating PAROMS data to 1 km ocean color grid;
- gridding and binning ocean color data to match the monthly time steps of the PAROMS model data;
- compare bias, error, and phenological variability of PAROMS inputs to global inputs for seascape classification.

We then produced two versions of the regionally downscaled model: Model 1 (Regional model) is based on seascape classification using standard (as global model) variables (chl-a, chromophoric dissolved organic matter, normalized fluorescent line height, sea surface temperature, salinity, sea surface height, and sea-ice concentration with the latter four from PAROMS models rather than remote sensing). Model 2 is a “Physics only” model and was explored to produce models that may be more suitable for the Arctic shoulder seasons (freeze-up and ice melt), during times of low solar angle or winter conditions and when remote sensing imagery and data are typically not available or unreliable. The Physics only model is based only on sea surface temperature, salinity, sea surface height, and sea ice concentration from PAROMS model output (Fig. 37).

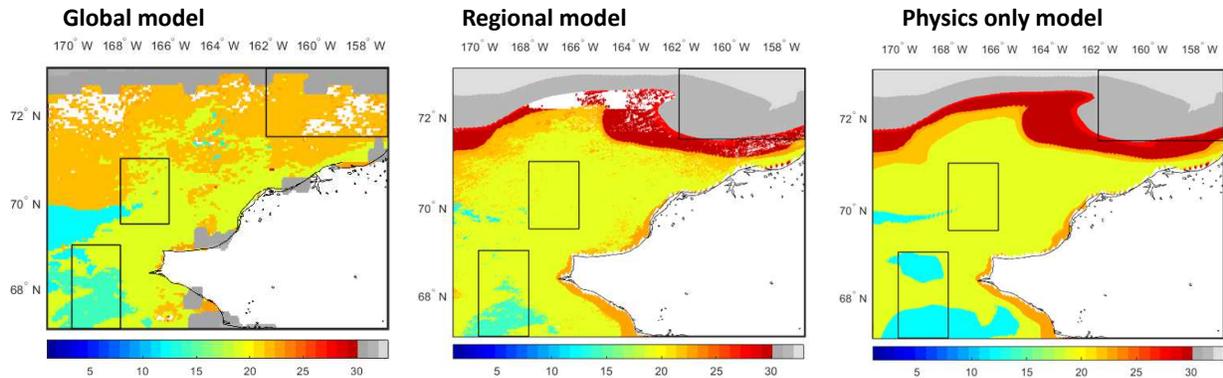


Figure 37. Dynamic seascape classifications for July 2017 from: The Global model (left), the Regional model (middle), and the Physics only model (right). Rectangles denote regions where seascape output or model fields were extracted. Seascape classifications given as color bars below each model output with the most relevant classifications given to the right. Model and remotely sensed data were specifically extracted for the regions indicated by the boxes, of which the two boxes in the Chukchi Sea represent the AMBON study region. Seascape classifications as in Fig. 35.

The comparison of the Global to the Regional model shows that while there is moderate coherence between the two models (some of the same major seascape classifications occur), the Regional model is better able to identify Arctic-specific and ecologically important seascapes such as ice edge and ice edge blooms (red colors), which were missed in the global model (Fig. 37). Similarly, the Global model overestimated regions where sea ice is present in the coastal regions (gray colors) and underestimated ice cover towards the central Arctic Basin (Fig. 37). High resolution seascape states relying on PAROMS models show slightly more variability in freshwater influenced seascapes (e.g., seascape 23, Arctic continental shelves). Importantly, they also highlight more coverage from higher productive seascapes (e.g., seascapes 28 and 30, ice-influenced seascapes). This is a direct influence of the higher resolution ocean color and ROMs input fields. Hence, the Regional model is very appropriate to use in the Arctic when aiming for linkages to biological communities. The Physics only model was less nuanced than the Regional model but still provided an excellent match with much of the same features and seascape distributions (Fig. 37). This is especially important during the fall season, when sea-ice has yet to form, leaving several months of open water that is invisible to passive remote sensing. Fall periods have physics that may be conducive for high primary production (high presence of seascapes 28 and 30), although there remains a need to sea-truth. Finally, the Northern Chukchi sea appears to be the region most affected by poor retrieval (Fig. 37). This confirms that a model output entirely from physical model data can be useful, especially for the shoulder seasons.

Keeping the separate southern and northern Chukchi Sea approach, we then compared timeseries of both the Regional and the Physics only model output for the northern and the southern Chukchi Sea (Fig. 38). These time series provide regional differences in seascape composition and their seasonal evolution. Using the Regional (or Physics only model, depending on season) will be useful for the next step, which is to link these seascape data with those of biological communities. Particularly, extracting PAROMS data for the northern and southern Chukchi Sea regions separately will result in more precise seascapes to match biological distributions.

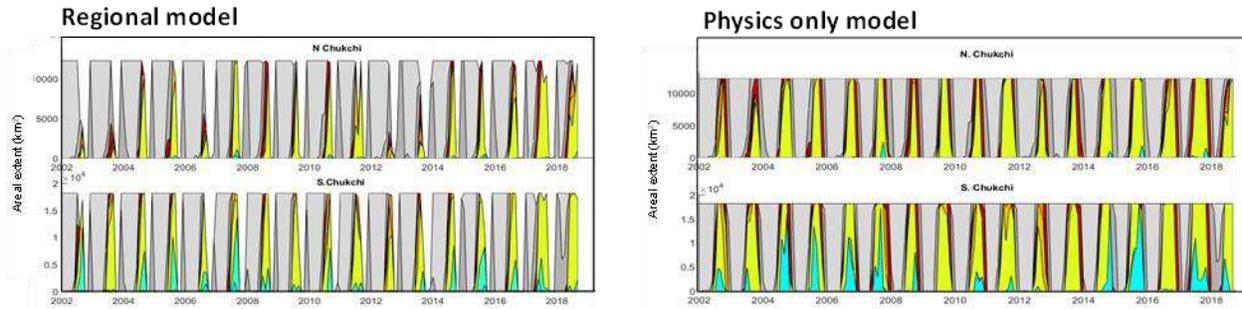


Figure 38. Changes in seascape areal extent through time (2002-2018) for: Northern Chukchi Sea (top) and Southern Chukchi Sea (bottom) from the regional model (left) and the physics only model (right). Seascape classification colors as in Fig. 35.

3.11 Diversity assessment across ecosystem components

At the end of the first AMBON project, we had collected diversity data from across multiple ecosystem components collected from the dedicated 2015 and 2017 cruises. We conducted an initial analysis at the end of the first AMBON phase, but then continued and completed the analysis across ecosystem components as an objective during this AMBON phase 2 project. The coordinated sampling across ecosystem components allowed us to compare species richness of microbes (bacteria, protists), zooplankton (small and large size groups), benthic macro-infauna and epifauna, demersal fish, and seabirds. Specifically, sampling in two years differed in their overall temperature regime, where 2017 was a warmer year than the colder year 2015 (Fig. 39). We found that diversity was higher in the warmer year, 2017, for the zooplankton and fish assemblages but was higher in the colder year, 2015, for bacteria, protists, epibenthos, and seabirds. There were no differences in diversity for macro-infauna between the two years. Areas of high diversity for bacteria, benthic macro-infauna, and epibenthic invertebrates were in the northern part of the study area while pelagic zooplankton and seabirds, as well as mobile demersal fish typically had higher diversity in the more southern study area (Fig. 40).

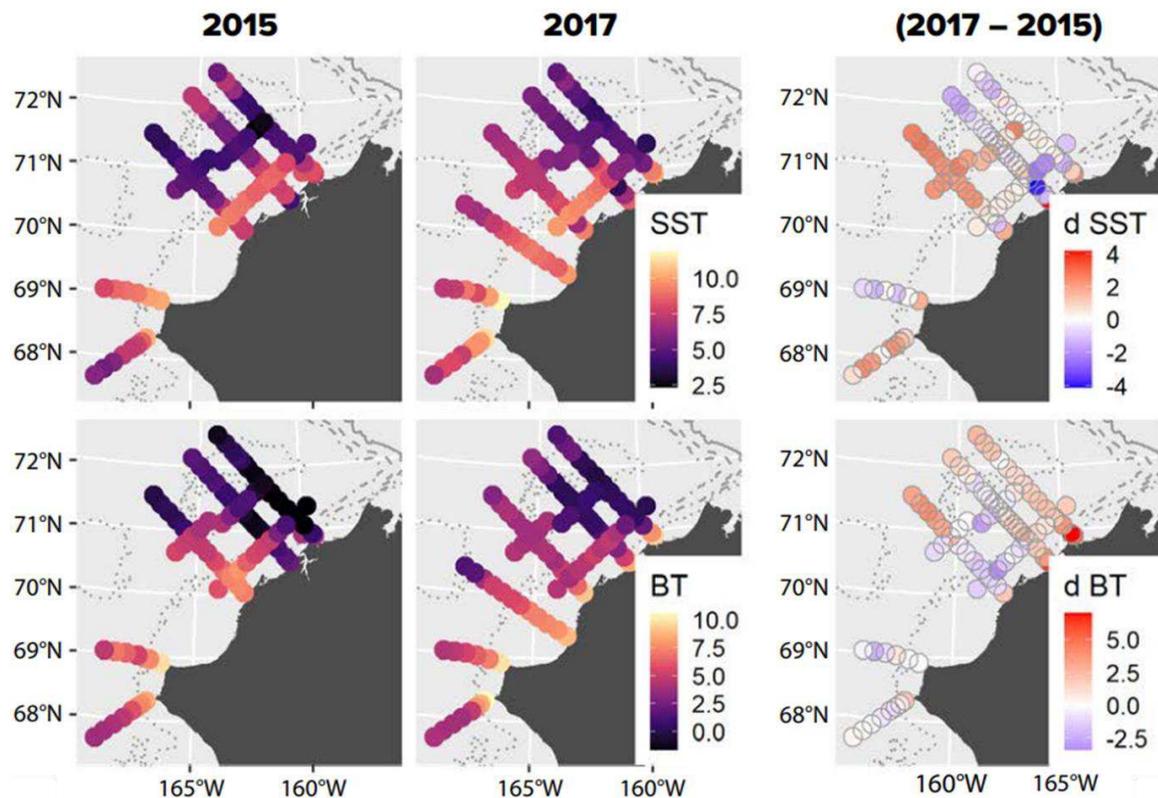


Figure 39. Sea surface temperatures (top row) and bottom water temperatures (bottom row) at sampling stations during AMBON cruises in 2015 (first column) and 2017 (second column), as well as the difference between the two years (third column). Positive values (red) indicate higher temperatures in 2017.

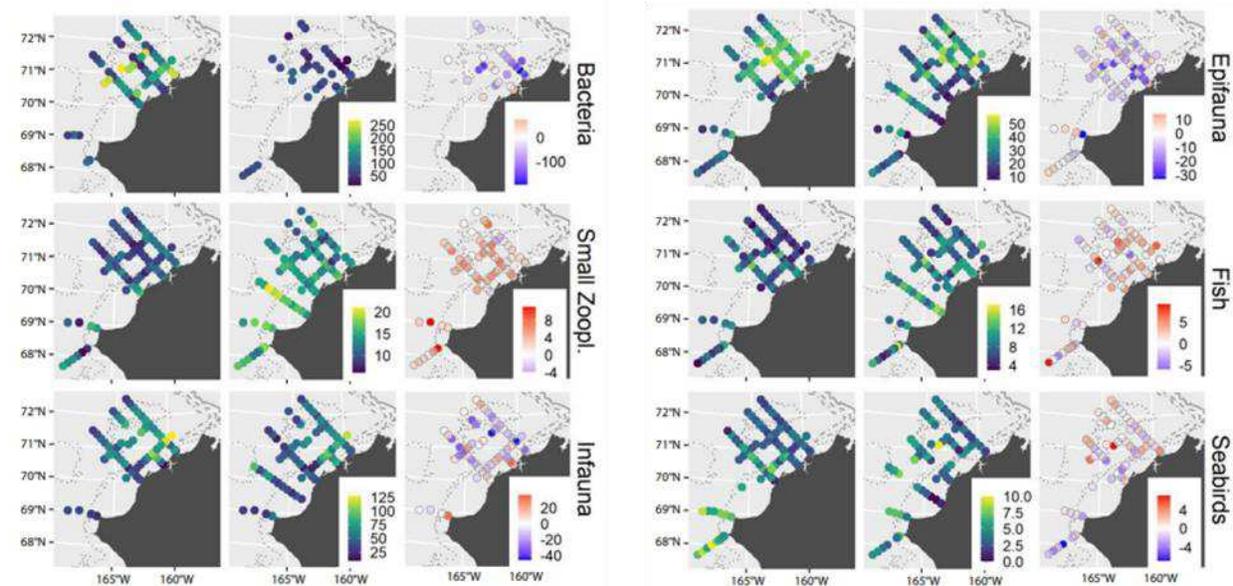


Figure 40. Spatial gradients in local species richness of six assemblages sampled during AMBON 2015 (left column) and 2017 (center column), with lighter (yellow) colors denoting higher species richness. Shading in the right column shows the differences in species richness between the two years (2017-2015 values), with blue colors indicating higher richness in 2015 (cold year).

For the analysis of species richness relationships with the environment, we included data on surface and bottom water temperature and salinities, integrated water column chlorophyll, some nutrient concentrations, sources of freshwater present in surface and bottom water (i.e., proportions of river runoff and sea ice melt), a stratification index computed as the mean water column density gradient, and sediment chlorophyll-a (for details, see Mueter et al. 2021a). To assess the strength of these species richness specifically to temperature and compare them between years, we fit linear regressions surface temperature (pelagic assemblages and seabirds) or bottom temperature (benthic assemblages) by sampling year. For most ecosystem components, temperature was a strong driver of species richness and accounted for most of the variability in most ecosystem components (Fig. 41). Local richness of benthic macro-infauna and epibenthos in both years and of large zooplankton in 2017 decreased significantly with temperature ($p < 0.001$), whereas local richness of fish in both years and of bacteria, protists, and seabirds in 2015 increased significantly with temperature ($p < 0.001$, $p = 0.034$, and $p = 0.005$, respectively) (Fig. 41). In contrast to large zooplankton, the local richness of small zooplankton increased significantly with temperature across the study region in 2017 ($p < 0.001$). Other environmental variables also played a role in richness for some of the assemblages, such as salinity (for macro-infauna, epifauna, fish, and seabirds), but temperature was the major driver and others did not explain significant variability in richness.

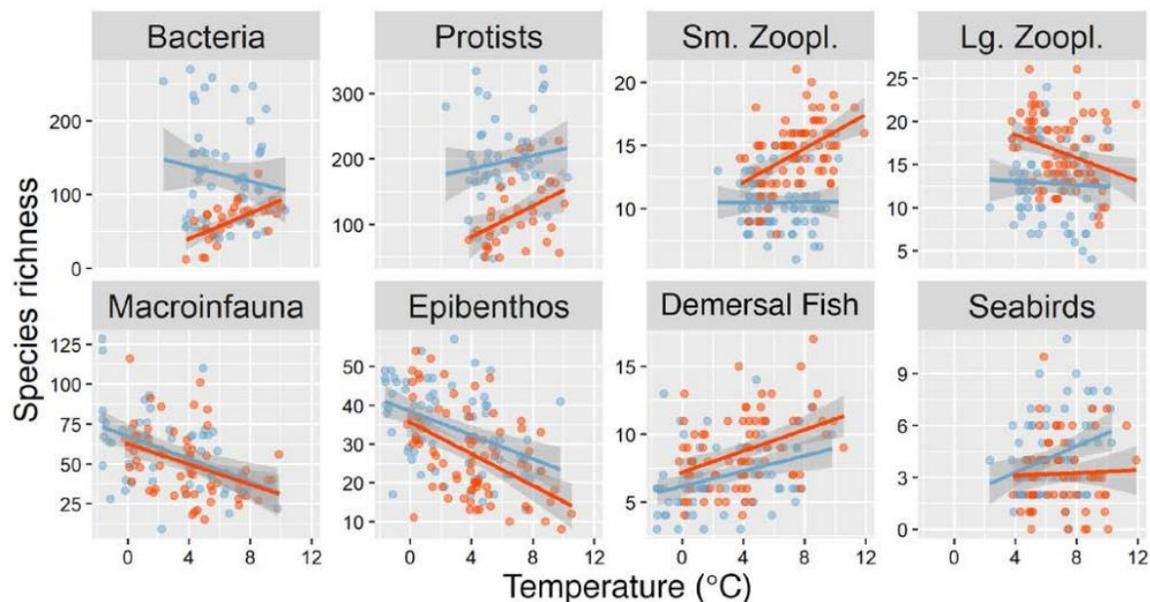


Figure 41. Species richness against temperature, with estimated linear relationships and 95% confidence bands by year (blue for 2015, orange for 2017). Bottom temperatures were used for benthic communities (macro-infauna, epibenthos, demersal fish), and sea surface temperatures for other assemblages.

Our results suggest that borealization of Arctic systems, defined as the increased influx of boreal species into the Arctic, may be influencing assemblages in the Chukchi Sea. Borealization is expected to occur when conditions in Arctic waters becomes more suitable for boreal (here, Pacific) species, and mostly relates to the temperature conditions (Mueter and Litzow 2008, Fossheim et al. 2015, Husson et al. 2024). Observed increases in the diversity of mobile demersal fish and small zooplankton is consistent with corresponding warming of the Chukchi shelf in 2017, and an influx of more boreal species (Mueter et al. 2021b, Axler et al. 2024). The reverse pattern observed for the more stationary benthic components suggest that benthic species are more likely influenced by bottom-up effects associated with warming, such as changes in biological rates, changes in the advective food supply, changes in pelagic-benthic

coupling (Feng et al. 2016, Grebmeier et al. 2018). The limited mobility and the lag time of increased larger larval supply from boreal species recruiting into the adult populations that were sampled suggest that actual borealization effects in benthic assemblages will have a longer lag period. In contrast, pelagic communities and seabirds responded more strongly and more immediately to changes in oceanographic conditions. Specifically, stronger advection in 2017 may have increased the transport of relatively rare zooplankton taxa of Pacific origin into the Chukchi Sea (Hunt et al. 2016). Seabirds are highly mobile, hence, their feeding distributions and abundances in the Chukchi Sea can respond to changes in their prey field (Kuletz et al. 2020). We found that species composition was related to the gradient from warm, saline Pacific water to cold, less saline Arctic water, likely reflecting associations between seabirds and their preferred prey. A decoupling of the seabird assemblage from other assemblages in 2017 suggests that seabirds were unable to fully adjust to changing prey conditions in 2017. Continued warming of the Chukchi Sea will likely result in further borealization, with differential impacts on pelagic and benthic communities.

4 Stakeholder Engagement and Networking

Regular monthly **PI meetings** were held virtually by zoom conference calls during the project period. The PI meeting calls served to communicate project progress, concerns, planning, coordination, and discussion of findings. In-person PI meeting was held in January 2020, 2021 and 2022 in Anchorage, AK, in conjunction with the Alaska Marine Science Symposium (AMSS) conference.

We continued to participate in monthly **xMBON** meetings and attended the in-person xMBON meetings during the project period. AMBON continues to contribute a polar perspective to the overall MBON group. We have also been involved in the various **MBON working groups**: Hopcroft and Iken were part of the original Biodiversity-Ecosystem-Function (BEF) working group led by Dr. Jeff Runge (University of Maine). Stafford was part of the Soundscape group led by Dr. Neil Hammerschlag. We continue to actively work with Dr. Maria Kavanaugh on Arctic seascapes. Galaska was part of the eDNA working group led by Dr. Francisco Chavez and Dr. Luke Thompson. Our data manager from AXIOM (Canino) was a member of the Data Management group led by Dr. Matt Biddle.

AMBON PI Cooper has been involved in planning for, and attended, the **Arctic Science Summit Week 2022** (March 26-April 1, 2022) in Tromsø, Norway. This meeting included a workshop on follow-on plans for the Arctic Action Plan for the UN Decade of Ocean Science for Sustainable Development. PIs Cooper and Grebmeier also attended the **Arctic Science Summit Week 2023** (17 - 24 February 2023) in Vienna, Austria. In order to advance discussions and begin to outline a roadmap towards realisation of a structure for international coordination of Arctic Ocean observing, the Arctic ROOS, in collaboration with partners around the globe, convened a session ‘Roundtable meeting: Towards a GOOS Regional Alliance (GRA) for the Arctic’. Both Cooper and Grebmeier represented the AMBON project during this Roundtable, with Grebmeier providing an oral presentation, and Cooper also being engaged as a member of the organizing committee.

Several AMBON PIs (Iken, Cooper, Kuletz) were members of the **Integrated Ecosystem Assessment (IEA) of the Northern Bering-Chukchi Seas**. This was a working group (WG44) approved by the PICES Governing Council. The WG44 met regularly (twice a year) and worked in between in subgroups to gather metadata information, conceptual models, analysis, and involvement of local stakeholders. AMBON datasets were provided for this metadata collection. The group recently completed the final report, which was subsequently accepted by the PICES Science Board 2024 meeting (WG44 PICES: <https://meetings.pices.int/members/working-groups/disbanded/wg44>). This report is now being prepared as a PICES Press article. In addition, AMBON PIs Grebmeier and Kuletz are involved with the **ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central**

Arctic Ocean, which is outside the AMBON study area but our increased understanding of processes and diversity of the shelf help understanding of the adjacent basin ecosystem.

AMBON PI Iken was appointed as a member of the National Academy of Sciences, Engineering and Medicine - **COSA committee** (Standing Committee on Environmental Science and Assessment for Ocean Energy Management). The committee meets up to three times a year in person (if possible) and holds monthly zoom calls. This committee provides ongoing assistance to the Bureau of Ocean Energy Management (BOEM) in its efforts to manage development of the nation's offshore energy resources in an environmentally and economically responsible way. The committee's tasks include:

- Convene experts from academia, industry, and other organizations to provide independent, technical input on issues of interest to BOEM's environmental studies and assessment programs, and potentially other programs;
- Facilitate stakeholder discussions of controversial issues;
- Enhance the understanding of developments in related fields of science and technology, and if warranted, to develop NRC studies on specific topics;
- Provide a venue for BOEM staff to meet and exchange information with staff from other federal agencies and help BOEM define its unique role in the interagency process;
- Facilitate the exchange of information and lessons learned with staff from other world class applied environmental studies and assessment programs with a view to assisting BOEM in being the best in such programs

AMBON PI Mueter is on the **NPFMC Scientific and Statistical Committee** and a liaison to the **North Pacific Fishery Management Council**. Of special note is a public workshop in February 2023 of the NPFMC Scientific and Statistical Committee that Mueter co-led on recent rapid ecosystem changes in the northern Bering Sea and Chukchi Sea to inform the Council about the resilience of current fisheries management to these changes. Presentations were given by various AMBON PIs. A detailed report was presented to the Council in April 2023.

AMBON PI Mueter also is a member of the ICES/PICES section on 'Climate Change Impacts on Marine Ecosystems', which is focused on modeling approaches. He has reported on AMBON results and modeling work to the group.

Communication of our study results to the local communities in the Bering-Chukchi Sea region is important. To that effect, AMBON PIs, especially Grebmeier and Danielson, have presented findings of our cruises through the UAF Nome Campus Strait Science lecture series after each of the cruises, with input from all other cruise participants.

AMBON PI Grebmeier is co-chair of the **Interagency Arctic Research Policy Committee (IARPC) Marine Ecosystem Community of Practice** to facilitate US-cross agency interactions on ecosystem topic. AMBON presented results on activities during one of the monthly webinars of this group.

5 Publications and Presentations

5.1 Publications

The following list of citations includes those that relied actively on data collection through the AMBON project, those that incorporated existing data derived from the AMBON project, and those where

knowledge obtained from the AMBON project was instrumental in the interpretation of larger-scope results. **AMBON PI names are bolded.**

- Chapman, Z.M., **Mueter, F.J.**, Norcross, B.L. and Oxman, D.S., 2023. Arctic cod (*Boreogadus saida*) hatching season and growth rates in the Bering, Chukchi and Beaufort seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, 207, 105226.
- Chavez, F., Miller, R., Muller-Karger, F., **Iken, K.**, Canonico, G., Egan, K., Price, J. and Turner, W., 2021. Marine Biodiversity Observation Network (MBON): An Observing System for Life in the Sea. *Oceanography*, 34(2), 12-15. <https://doi.org/10.5670/oceanog.2021.211>.
- Clairbaux, M., Rönkä, M., Anker-Nilssen, T., Artukhin, Y., Danielsen, J., Gavrilov, M., Gilchrist, G., Hansen, E.S., Hedd, A., Kaler, R. and **Kuletz, K.**, 2024. An ecologically sound and participatory monitoring network for pan-Arctic seabirds. *Conservation Biology*, 38(6), e14287.
- Cooper, L.W.** and **Grebmeier, J.M.**, 2022. A chlorophyll biomass time-series for the Distributed Biological Observatory in the context of seasonal sea ice declines in the Pacific Arctic region. *Geosciences*, 12(8), 307.
- Cooper, L.W.**, Magen, C. and **Grebmeier, J.M.**, 2022. Changes in the oxygen isotope composition of the Bering Sea contribution to the Arctic Ocean are an independent measure of increasing freshwater fluxes through the Bering Strait. *Plos one*, 17(8), e0273065.
- 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. Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves. *Deep Sea Research Part II: Topical Studies in Oceanography*, 177, 104781.
- Danielson, S.L.**, **Grebmeier, J.M.**, **Iken, K.**, Berchok, C., Britt, L., Dunton, K.H., Eisner, L., Farley, E.V., Fujiwara, A., Hauser, D.D. and Itoh, M., 2022. Monitoring Alaskan Arctic Shelf ecosystems through collaborative observation networks. *Oceanography*, 35(3/4), 198-209. <https://doi.org/10.5670/oceanog.2022.119>
- Galaska, M.P.**, S.D. Brown, and S.M. McAllister. 2023. Monitoring biodiversity impacts of a changing Arctic through environmental DNA. *Oceanography*, 36(2-3), 110. <https://doi.org/10.5670/oceanog.2023.221>
- González, S., Horne, J.K., **Danielson, S.L.**, Lieber, L. and López, G., 2022. Representative range of acoustic point source measurements in the Chukchi Sea. *Elementa – Science of the Anthropocene*, 10(1), 00055.
- 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. and **Iken, K.**, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, 1-7.
- Husson, B., Bluhm, B.A., Cyr, F., **Danielson, S.L.**, Eriksen, E., Fossheim, M., Geoffroy, M., **Hopcroft, R.R.**, Ingvaldsen, R.B., Jørgensen, L.L. and Lovejoy, C., Meire, L., **Mueter, F.**, Primicerio, R., and Winding, M. 2024. Borealization impacts shelf ecosystems across the Arctic. *Frontiers in Environmental Science*, 12, 1481420.
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patterns of marine vertebrates in Arctic and Subarctic ecosystems. *Frontiers in Environmental Science*, 12, 1434549.

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- Stafford, K.M.,** Farley, E.V., Ferguson, M., **Kuletz, K.J.** and Levine, R., 2022. Northward range expansion of subarctic upper trophic level animals into the Pacific Arctic region. *Oceanography*, 35(3/4), 158-166. <https://doi.org/10.5670/oceanog.2022.101>.
- Stafford, K.M.,** Melling, H., Moore, S.E., Berchok, C.L., Braen, E.K., Brewer, A.M. and Kimber, B.M., 2022. Marine mammal detections on the Chukchi Plateau 2009–2020. *The Journal of the Acoustical Society of America*, 151(4), 2521-2529.
- Sutton, L., **Mueter, F.J.,** Bluhm, B.A. and **Iken, K.,** 2021. Environmental filtering influences functional community assembly of epibenthic communities. *Frontiers in Marine Science*, 8, 736917.
- Gall, A.E., Prichard, A.K., **Kuletz, K.J.** and **Danielson, S.L.,** 2022. Long: Influence of water masses on the summer structure of the seabird community in the northeastern Chukchi Sea. *Plos One*, 17(4), e0266182.
- Zinkann, A.C., Wooller, M.J., Leigh, M.B., **Danielson, S.,** Gibson, G. and **Iken, K.,** 2022. Depth distribution of organic carbon sources in Arctic Chukchi Sea sediments. *Deep Sea Research Part II: Topical Studies in Oceanography*, 199, 105076.

5.2 Major Reports

- Labunski, E. A., **K. J. Kuletz,** R. Lanctot, S. Saalfeld, T. C. Morgan, R. L. McGuire, and A. E. Gall. 2022. Marine Bird Distribution and Abundance in the Northern Bering and Chukchi Seas: Final Report. US Dept. of the Interior, Bureau of Ocean Energy Management, Alaska OCS Region. OCS Study BOEM AK-17-03. Provided to BOEM by the U.S. Fish and Wildlife Service, xv + 175 pp.
- Marsh, J.M., Pirtle, J.L., **Mueter, F.J.,** and Harris J. 2023. Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area. Report submitted to the North Pacific Fisheries Management Council. January 2023
- Logerwell, E., Rand, K. (eds) 2024. PICES Report of Working Group 44 on Integrated Ecosystem Assessment of the Northern Bering and Chukchi Seas. Accepted Final Report. In prep for publication as a PICES Press article. (with contributions by **Iken, Cooper, Kuletz**)

5.3 Presentations

- Sutton L, **Iken K, Mueter F,** Bluhm B. 2020. The influence of environmental drivers on functional diversity across Alaskan Arctic epibenthic shelf communities. Poster presentation, Alaska Marine Science Symposium, Anchorage AK, 2020

- Sutton L, **Iken K**. 2020. Environmental filtering of functional composition in Alaskan Arctic shelf epibenthos. Poster presentation, World Conference on Marine Biodiversity, virtual conference, November 2020
- Cooper L, Grebmeier G**, Cooper R, Gaffey C, Goethel C, Maisch J, Sandy S, Shipton P, **Danielson S, Iken K**. 2021. Late Season Observations in the Northern Bering and Chukchi Seas: Initial Results from an October 2020 Research Cruise. Oral presentation, Alaska Marine Science Symposium, virtual conference, January 2021
- Sutton L, **Iken K**. 2021. Environmental filtering of functional composition in Alaskan Arctic shelf epibenthos. 2021. Oral presentation, Alaska Marine Science Symposium, virtual conference, January 2021
- Kuletz K**, Cushing D, **Mueter F**, Osnas E, Kimmel D, Labunski E, Levine R, De Robertis A. 2021. Peak ocean temperatures cap long-term warming in the eastern Pacific Arctic and slams seabirds. World Seabird Conference (virtual), Symposium on “Mechanisms by which extreme heat anomalies impact seabirds”, 5 October 2021.
- Sutton L, **Iken K, Mueter F**. 2022. Benthic habitat suitability based on functional traits in a changing Arctic marine ecosystem. Alaska Marine Science Symposium, virtual, January 2022. Oral presentation
- Mueter FJ, Iken K, Cooper LW, Grebmeier JM, Kuletz KJ, Hopcroft RR, Danielson SL**, Collins RE, Cushing DA. 2021. Changes in diversity and species composition across multiple assemblages in the northeast Chukchi Sea during two contrasting years are consistent with borealization. Arctic marine ecosystem. Alaska Marine Science Symposium, virtual, January 2022. Oral presentation
- Danielson SL, Iken K**. 2022. Arctic Marine Biodiversity and Ecosystem Structure – Data Analysis & Synthesis. Coastal Marine Institute Annual Review, virtual. Oral presentation
- Sutton L, **Iken K, Mueter F**. 2022. Benthic habitat suitability based on functional traits in a changing Arctic marine ecosystem. Ocean Sciences Meeting, virtual, February 2022. Oral presentation
- Iken K, Mueter FJ, Cooper LW, Grebmeier JM, Kuletz KJ, Hopcroft RR, Danielson SL**, Collins RE, Cushing DA. 2022. Changes in diversity and species composition across multiple assemblages in the northeast Chukchi Sea during two contrasting years are consistent with borealization. Ocean Sciences Meeting, virtual, February 2022. Oral presentation
- Iken K**. 2022. Systems change in the Arctic Ocean ecosystem - Identifying gaps and synergies with existing Arctic Ocean research. National Geographic & Rolex Perpetual Planet Expeditions Arctic Science Planning meeting, virtual, March 2022. Oral presentation
- Iken K, Mueter F, Kavanaugh M, Kuletz K, Hopcroft R**, Sutton L, **Grebmeier J, Cooper L, Danielson S, Galaska M, Stafford K**. AMBON – What’s next. Oral presentation. xMBON Synthesis Workshop, November 2022, Monterey Bay CA
- Iken K**. 2022. Recent scientific advancements in the Chukchi and Beaufort seas. Invited speaker, oral presentation. 5th pan-Arctic synthesis workshop (Motovun, Croatia).
- Gall A, Prichard A, **Kuletz K, Danielson S**. 2023. What structures the seabird communities in the Chukchi Sea? Alaska Marine Science Symposium, Jan 2023, Anchorage AK.
- Hoover B, Arimitsu M, Piatt J, **Kuletz K**, Renner H, Garcia-Reyes M, Sydeman W. 2023. Modeling seabird distribution and abundance in Alaska’s marine ecosystems: synthesis of change. Alaska Marine Science Symposium, Jan 2023, Anchorage AK.
- Sullender B, Kapsar K, **Kuletz K**. 2023. Seabird-vessel traffic risk analysis for Alaska’s oceans. Alaska Marine Science Symposium, Jan 2023, Anchorage AK.

- Iken K, Cooper L, Danielson S, Galaska M, Grebmeier J, Hauser D, Hopcroft R, Kavanaugh M, Kuletz K, Mueter F, Stafford K, Wisdom S, Whiting A.** 2023. AMBON – linking biodiversity observations in the Arctic. Poster presentation, Alaska Marine Science Symposium, January 2023, Anchorage AK
- Danielson S, Gonzalez S, Hauri C, Horne J, Iken K, Lalande L, Mahoney A, Sandy S, Stafford K.** 2023. Updates from the CEO: Recent Results, New Sensor Configurations, Plans and Activities. Poster presentation, Alaska Marine Science Symposium, January 2023, Anchorage AK
- Sutton L, **Mueter F**, Hauri C, Pages R, **Iken K.** 2023. Predicting epibenthic functional distribution on changing Arctic shelves. Alaska Marine Science Symposium, Jan 2023, Anchorage AK.
- Kuletz K.** 2023. Breaching the border & shifting boundaries: 50 years of change in northern oceans. Plenary talk for 50th annual meeting of the Pacific Seabird Group, San Diego, CA, Feb 15-17, 2023.
- Iken K, Kavanaugh M, Grebmeier J, Cooper L, Galaska M, Mueter F, Hauser D, Danielson S, Stafford K, Kuletz K, Hopcroft R, Whiting A.** 2024. AMBON – linking biodiversity observations in the Arctic. Poster presentation, NASA Biodiversity & Ecological Conservation (BDEC) meeting, May 2024, Silver Spring, MD
- Galaska M, Iken K.** 2024. AMBON – linking biodiversity observations in the Arctic. Oral presentation, ONR Marine Mammals and Biology meeting, April 2024, Arlington, VA
- Iken K, Galaska M, Grebmeier J, Cooper L, Mueter F, Hauser D, Danielson S, Kavanaugh M, Stafford K, Kuletz K, Hopcroft R, Whiting A.** 2024. AMBON – linking biodiversity observations in the Arctic. Poster presentation, xMBON meeting, March 2024, New Orleans, LA
- Danielson S, Hedstrom K, Hennon T, Sandy S, Iken K.** 2024. Winter refugia for subarctic species in the Pacific Arctic: A newly emerging seafloor habitat? Oral presentation, Alaska Marine Science Symposium, January 2024, Anchorage AK
- Stowell M, Copeman L, Cooper D, Suryan R, **Iken K.** 2024. Shrimp lipid biomarkers as metrics of groundfish prey resources in the Bering Sea. Poster presentation, Alaska Marine Science Symposium, January 2024, Anchorage AK
- Gonzalez S, Thorson J, Veron M, Barnett L, **Cooper L, Danielson S, Iken K, Grebmeier J,** Eisner L, Kimmel D, Logerwell L, Lomas M, McCabe R, Nielsen J, Yasumiishi E. 2024. Spatiotemporal variability of Pacific Arctic marine ecosystems. Poster presentation, Alaska Marine Science Symposium, January 2024, Anchorage AK
- Sutton L, Forster C, **Iken K, Mueter F.** 2024 The role of static and dynamic drivers in shaping Arctic fish functional trait diversity. Poster presentation, Alaska Marine Science Symposium, January 2024, Anchorage AK
- Iken K.** 2024. Coastal observing networks in the Alaskan Arctic. ARC-BON inaugural workshop, January 2024, Copenhagen, Denmark.
- Kapsar, K. Sullender, B., Kuletz, K. 2024. Quantifying risk of vessel encounters with sea ducks in the North Pacific: a multi-scale seasonal analysis of Alaskan oceans. 2024. 7th International Sea Duck Conference. Virtual, January 2024.
- Kuletz, K., Hoover, B., Koval, G., Thompson, S.A., García-Reyes, M., Arimitsu, M., Piatt, J.F., and Sydemann. 2025. Seasonal redistribution of seabirds across Alaska’s marine ecosystems with respect to ocean temperatures, 2000-2021. 2025. Pacific Seabird Group, San Jose, Costa Rica, January 2025.
- Iken, K., Gonzalez, S., Logerwell, E. Trends in epibenthic biomass and community structure in the Chukchi Sea. Oral presentation Alaska Marine Science Symposium, January 2025, Anchorage, AK.

AMBON PIs **Danielson, Iken, Cooper, and Grebmeier** jointly chaired a session during the Ocean Sciences Meeting in March 2022: Session HL03 Ecosystem processes and structure in a changing Arctic. The session was a huge success with four oral sections and one poster session.

6 Datasets

Table 3. Datasets archived during the AMBON project.

Project	PI	Dataset	Cruise Year	Archive Status	DOI link	PID Link	Resource Title
CEO / AMBON - Oceanographic data	Danielson	year-round hydrography	2020	Archived with RW	https://doi.org/10.24431/rw1k7dw	https://search.dataone.org/view/10.24431/rw1k7dw	CTD cast and bottle data from a collaborative Chukchi Sea research cruise on R/V Norseman II, October 2020
AMBON / DBO - Sediment characteristics	Cooper, Grebmeier	surface sediment data	2020	archived at ADC	https://doi.org/10.18739/A2H70826B	https://arcticdata.io/catalog/view/doi:10.18739/A2H70826B	Surface sediment samples collected from the Norseman II Cruise, 2020, Northern Bering Sea to Chukchi Sea
AMBON / DBO Oceanographic data	Cooper, Grebmeier	CTD water samples	2020	archived at ADC	https://doi.org/10.18739/A2MW28G7F	https://arcticdata.io/catalog/view/doi:10.18739/A2MW28G7F	Discrete water samples collected from the Conductivity-Temperature-Depth (CTD) rosette at specific depths, Norseman II, Northern Bering Sea to Chukchi Sea, 2020
AMBON / DBO - Sediment characteristics	Cooper, Grebmeier	surface sediment data	2021	archived at ADC	https://doi.org/10.18739/A2SN0160Z	https://arcticdata.io/catalog/view/doi%3A10.18739%2FA2SN0160Z	Surface sediment samples collected from the Research Vessel Sikuliaq, Northern Bering Sea to Chukchi Sea, 2021
AMBON / DBO - Oceanographic data	Cooper, Grebmeier	CTD water samples	2021	archived at ADC	https://doi.org/10.18739/A2XD0R04Q	https://arcticdata.io/catalog/view/doi%3A10.18739%2FA2XD0R04Q	Discrete water samples collected from the Conductivity-Temperature-Depth (CTD) rosette at specific depths, Research Vessel Sikuliaq, Northern Bering Sea to Chukchi Sea, 2021
AMBON - SAS Oceanographic data	Danielson	CTD water samples	2021	archived at R2R	https://doi.org/10.7284/150883	https://www.rvdata.us/search/files/150883	CTD (SeaBird SBE-911+) data as collected during the cruise SKQ2021155
AMBON - Oceanographic data	Danielson	CTD water samples	2022	archived at ADC	https://doi.org/10.18739/A2V97ZT3G	https://search.dataone.org/view/doi:10.18739%2FA2V97ZT3G	Water column profile data from Conductivity-Temperature-Depth instrument on 2022 Synoptic Arctic Survey Cruise HLY2202 to the North Pole aboard USC/GC Healy
AMBON - eDNA	Galaska	CTD eDNA	2020	archived in NCBI	n/a	https://www.ncbi.nlm.nih.gov/bioproject/982176	eDNA metabarcoding of samples in the Bering and Chukchi Seas
AMBON - Zooplankton data	Hopcroft	abundance & biomass	2020	Archived with RW	https://doi.org/10.24431/rw1k9gh	https://doi.org/10.24431/rw1k9gh	Zooplankton Species Distribution and Abundance Data, with 150µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, October 2020
AMBON - Zooplankton data	Hopcroft	abundance & biomass	2021	Archived with RW	https://doi.org/10.24431/rw1k9gi	https://doi.org/10.24431/rw1k9gi	Zooplankton Species Distribution and Abundance Data, with 150µm plankton net, Arctic Marine Biodiversity Observing Network (AMBON) Chukchi Sea research cruise, November 2021.

RW: AOS Research Workspace; ADC: Arctic Data Center; NCBI: National Center for Biotechnology Information

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BOEM Environmental Studies Program

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