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The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction

ABSTRACT

The Distributed Biological Observatory (DBO) is a change detection array for select ecosystem variables along eight sampling transects in the Pacific Arctic Region (PAR). The overall objective of the DBO is to provide for the detection and consistent monitoring of the biophysical responses to major reductions in seasonal sea ice and concomitant increases in seawater temperatures observed across the region. A key uncertainty is how the PAR marine ecosystem is responding to these shifts in the timing of spring sea-ice retreat and/or delays in fall sea-ice formation. Variations in upper ocean hydrography, stratification, light penetration, planktonic production, pelagic-benthic coupling, and sediment carbon cycling are all influenced by sea ice and temperature changes. Observations of reduced sea ice extent/duration and seawater warming are linked to shifts in species composition and abundance, as well as northward range expansions in some upper trophic predators (e.g. humpback whales and commercially harvested fish), generally with negative impacts on ice-dependent species such as ice-associated seals and walruses. Some distributional shifts may be driven by changes in lower trophic level productivity that directly cascade into upper trophic levels. This special issue is a result of the international effort by participating scientists to implement a coordinated DBO that will meet these needs to understand the ecosystem responses to changing sea ice and thermal regimes. The key geographical focus is on the biologically productive waters in the PAR that are influenced by the inflow of North Pacific water through Bering Strait. Papers in this volume are based upon selected biological measurements at multiple trophic levels, together with appropriate hydrographic surveys and satellite observations. The DBO is developing into a significant national and international change detection resource for the identification and consistent monitoring of marine biophysical responses to climate change, with ongoing plans to expand into a pan-Arctic biological observing network.

1. Introduction

The Distributed Biological Observatory (DBO) is an organizing framework for consistent biophysical sampling along eight transects in the Pacific Arctic Region (PAR). The overarching goal of the observatory is to establish a functioning "change detection array" along a latitudinal gradient extending from the northern Bering Sea through the Chukchi Sea and into the Beaufort Sea (Fig. 1). The DBO is thus building a biologically-oriented Arctic marine observatory system with consistent time series data within the remote, but rapidly changing PAR (Moore and Grebmeier 2018). Standardized measurements were initiated in 2010 in five regions in the northern Bering and Chukchi seas (DBO 1–5). Transects and stations were selected based upon known high productivity, biodiversity, and/or rates of biological change. In 2015, three additional regions (DBO 6–8) were added to sample the Beaufort Sea along a longitudinal gradient. Currently Canadian colleagues are working to expand DBO studies from the Pacific DBO into the Canadian Archipelago and Baffin Bay. This expansion is complemented by a similar approach in the Eurasian Arctic where an Atlantic DBO is being launched (Reigstad and Ingvaldsen, 2017). The DBO network could also be an example of a shared sampling and data product framework for coordination of international research efforts in the Central Arctic Ocean and its adjacent slope regions (NOAA, 2018; Anderson et al., 2018) that would ultimately help to develop a pan-Arctic biological observing system.

The PAR has had the most spatially extensive loss of seasonal sea ice of any of the Arctic marginal seas (Frey et al. 2015, 2018). The northern Bering and Chukchi seas are among the most productive marine ecosystems in the Arctic (Grebmeier et al. 2006, 2015a, Hill et al. 2018) and are important carbon sinks and seasonal sources of organic material. The ecosystems in the PAR are responding to changing seawater temperature regimes, currents, and ocean acidification. As a result, these shelves are prominent areas for observing climate change and feedback regulation (e.g. impacts on ice cover/albedo and CO_2 sequestration (Frey et al., 2014; Mathis et al., 2014; Moore et al., 2014; Grebmeier et al., 2015a, 2018). The biological measurements made along the DBO transects focus on both lower trophic levels and shipboard surveys of upper trophic levels (Moore and Grebmeier, 2018). As an "inflow shelf" responding to the influence of the Pacific Ocean (Carmack and Wassmann, 2006), the Bering and Chukchi seas are sites of enhanced primary productivity and major biogeochemical transformations in elemental stoichiometry (Hill et al., 2018). For example, N/P ratios of water column nutrients shift downward as water flows northward in response to denitrification in the sediments, and variations in carbonate saturation state reflect differences in carbonate buffering capacity among melting sea ice, runoff, and seawater (Mathis et al. 2014, Yamamoto-Kawai, 2016). The PAR is also a major seasonal habitat for globally significant populations of marine mammals and seabirds that annually migrate from as far away as the sub-tropics and even the Southern Hemisphere, respectively, to the Arctic to forage for food (Moore et al., 2014). In addition, mooring data are becoming increasingly available for all but DBO region 7, which enables the integration of seasonal DBO sampling into longer-term seasonal, annual, and interannual perspectives (e.g. Itoh et al., 2015; Nishino et al., 2016; Yamamoto-Kawai, 2016; Hauri et al., 2018).

Recent analyses (resolvable on decadal time frames) demonstrate that seasonal sea-ice extent and volume is declining in the PAR, both resulting from earlier sea-ice retreat, reduced Arctic multi-year ice, and

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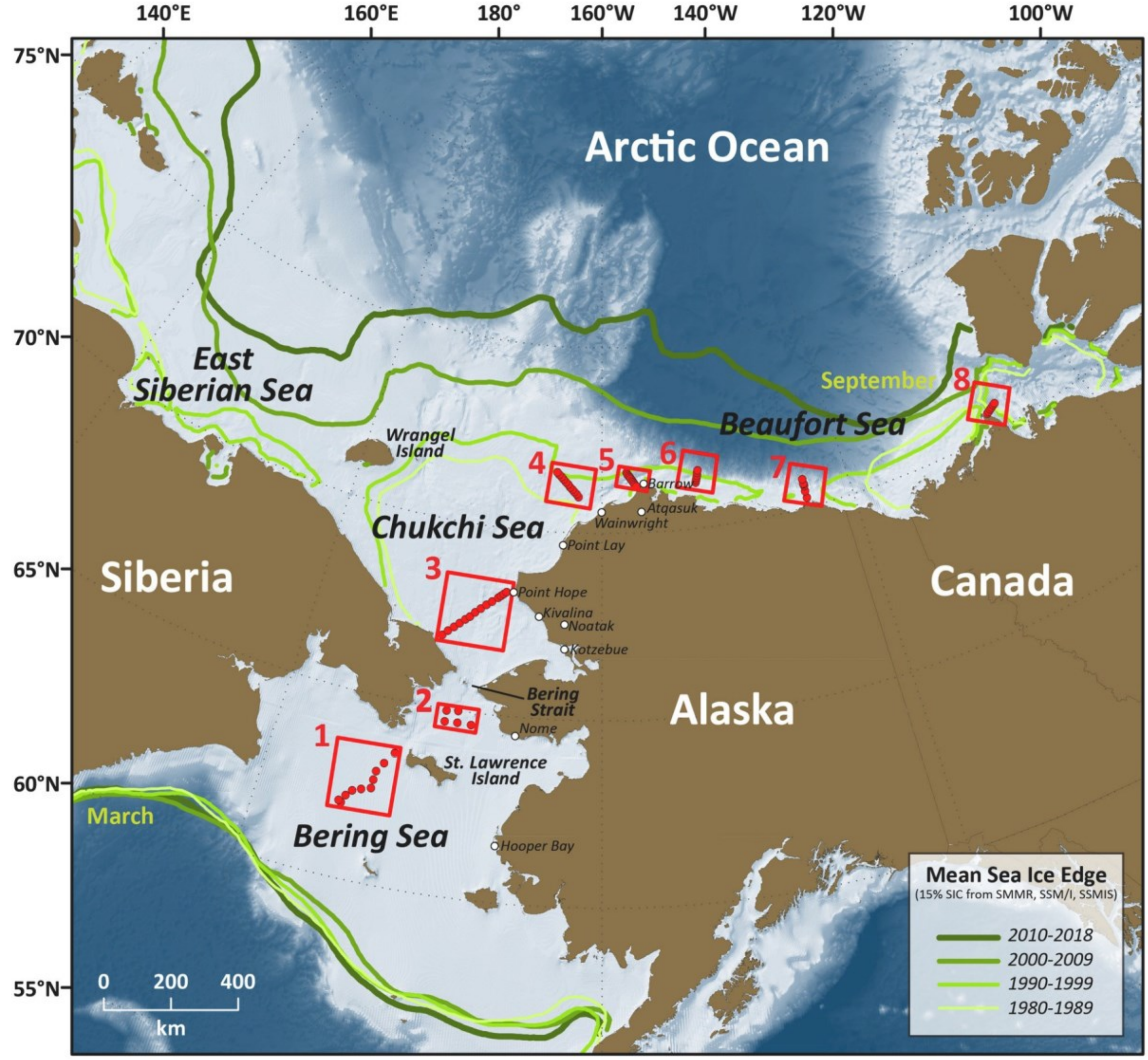

Fig. 1. The eight sampling regions of the Distributed Biological Observatory (DBO) extending from the northern Bering Sea into the Beaufort Sea in the Pacific Arctic Region that are focused on ‘hotspots’ of biological productivity and biodiversity. Maximum and minimum median ice extent based on SMMR, SSM/I, and SSMIS satellite-derived sea-ice concentrations (1979–2018) are also shown on this figure (updated from Moore and Grebmeier, 2018).

new, more northerly limits to sea ice in the late summer, which commonly now retreats off the continental shelf (Stroeve et al., 2014; Frey et al., 2014, 2015, 2018; Wood et al., 2015). The recent shifts in seasonal sea-ice cover since 2013 (Fig. 2) are having profound consequences by increasing seasonal phytoplankton production regionally (Arrigo et al., 2014; Frey et al., 2014, 2015, 2018) as well affecting upper trophic level species (Moore et al., 2014; Grebmeier et al., 2015a; Grebmeier et al., 2018), including marine mammals harvested locally by indigenous communities. In short, many organisms, from microplankton to top predators are changing their distribution, migration and foraging patterns (Moore and Stabeno, 2015; Moore et al., 2018a). However, key uncertainties remain because productivity may change as sea ice declines and penetration of sunlight into open water increases (Arrigo and van Dijken, 2015; Hill et al., 2018), but the trajectory of impacts to food web structure is unclear. The current transition of the DBO research framework from core data collection to include process studies and associated modeling will facilitate a better understanding of the status and change of this productive system.

One of the pressing needs for evaluating climate change impacts on biological systems in the Arctic (and globally) is the need for sustained observations of changes in biological systems. Biological observations cannot be automated to the same extent as many physical measurements can (e.g. salinity and temperature on moorings). As a result, there is much less scientific documentation of how biological systems are changing and/or adapting as a result of environmental change. Internationally, DBO sampling occurs by coordination through the Pacific Arctic Group (PAG), which is a network of scientific sampling and research planning undertaken by scientists and institutions from Canada, China, Japan, Korea, Russia and the United States.

The core DBO standardized ship-based sampling measures agreed to in the PAG forum include: (1) hydrography with conductivity-temperature-depth and acoustic Doppler current profiler velocity measurements, (2) chlorophyll, (3) nutrients, (4) ice algae/phytoplankton (size, biomass and composition), (5) zooplankton (size, biomass and composition), (6) benthos (size, biomass and composition), and (7) seabird and marine mammal observations (standard transects). With multiple occupations of various DBO transects, the seasonal changes in the Pacific Arctic are being elucidated as indicated in Fig. 3. Additional carbon-based measurements, such as particulate organic carbon, dissolved inorganic carbon, and dissolved organic carbon, are being collected by some participants in the DBO network and are encouraged as the DBO expands. The current observations identified the seasonal freshening and warming Pacific seawater that flows northward from spring to fall, with impacts on both plankton and benthic prey bases for

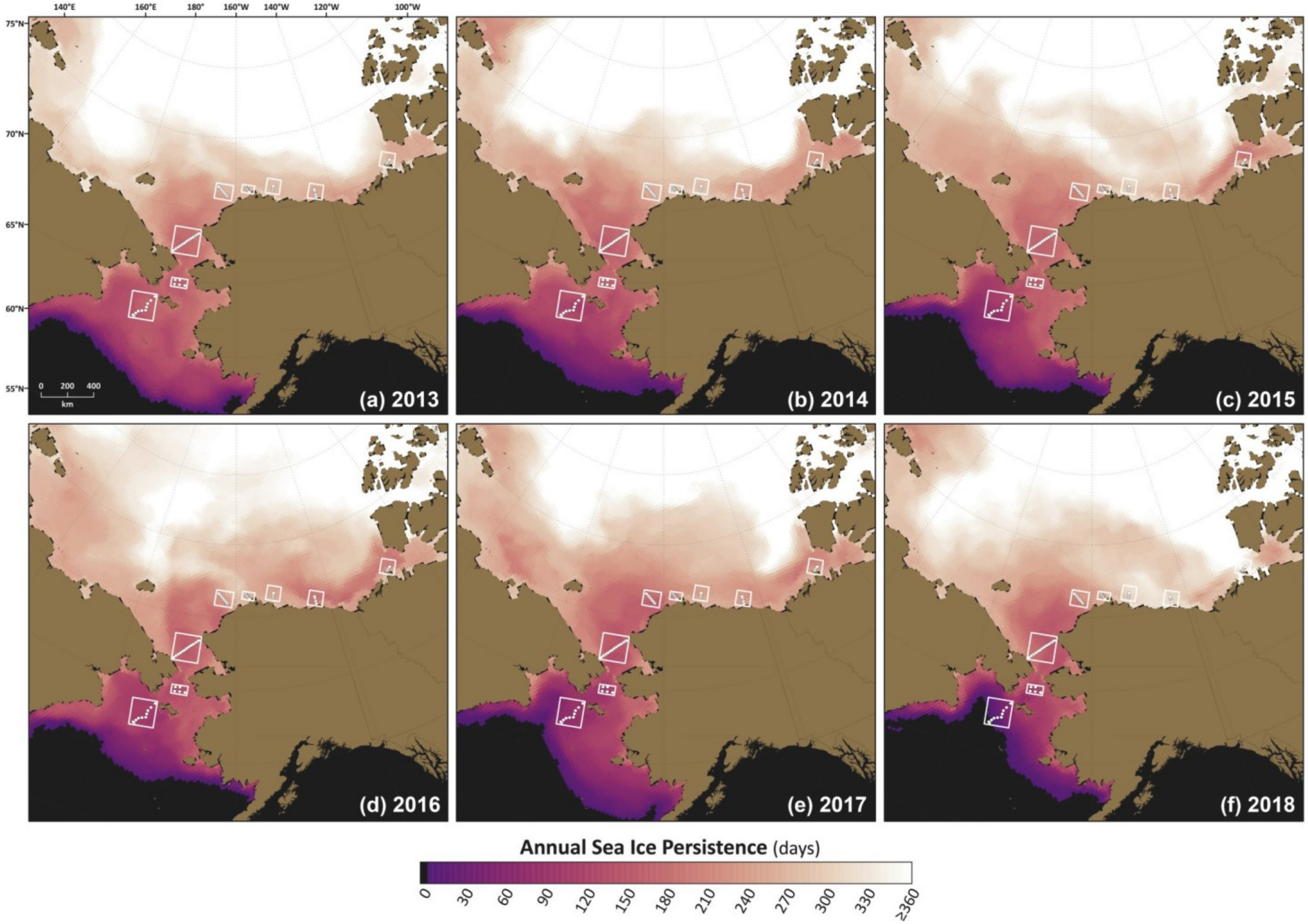

Fig. 2. Annual sea-ice persistence (number of days each year of sea-ice presence) across the DBO1–8 regions in the Pacific Arctic from 2013–2018. Pixels were specified as ice-covered if daily satellite-based SSM/I and SSMIS sea-ice concentration values were at least 15%. The 8 DBO regions include the sampling sites and associated bounding boxes.

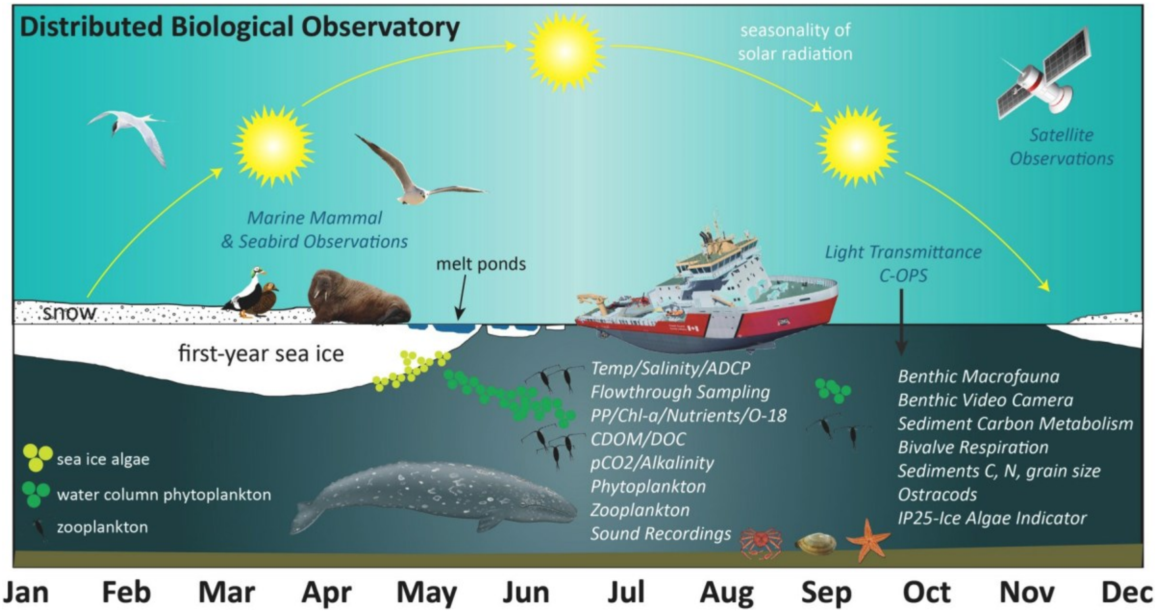

Fig. 3. Seasonality schematic of key sampling components of the Distributed Biological Observatory in the Pacific Arctic Region. Key: C-OPS=Compact-Optical Profiling System, Temp= Temperature, ADCP= Acoustic Doppler Current Profiler, C=Carbon, CDOM=Chromophoric Dissolved Organic Matter, Chl-a=Chlorophyll a, DOC=Dissolved Organic Carbon, IP-25=Ice proxy with 25 C atoms, N=Nitrogen, O-18=Oxygen-18/oxygen-16 ratios, PP=Primary Production. All lower taxa analyses include composition, abundance and biomass data.

larger marine mammals and seabirds (e.g. Grebmeier et al., 2015a,b, 2018; Itoh et al., 2015; Moore et al., 2014: Nishino et al., 2016; Yamamoto-Kawai et al., 2016; Moore and Grebmeier, 2018). Secondary, ship-based sampling efforts have also been integrated into the DBO effort through collaboration with US Bureau of Ocean Energy Management support, including the Arctic Ecosystem Integrated Survey (ArcticEis) (2012–2016) and ArcticEis2 (2017–2022) projects. Data from ArcticEis projects include fishery acoustics and periodic bottom trawling (Mueter et al., 2017).

This DBO special issue covers topics from physical oceanography, lower trophic level plankton and benthic fauna, to upper trophic level fish, seabird and marine mammals. Multiple papers also evaluated the capability of the DBO sampling approach to meet focused regional sampling needs and to consider the appropriate scales to evaluate the status and changes to the Pacific Arctic marine ecosystem as an observing system. We highlight here the specific contributions made in this first special DBO issue.

2. Sea Ice and Physical Oceanography

Hydrographic data from the DBO network document seasonal changes from spring to summer along a latitudinal gradient in the PAR. Trends from south to north in sea-ice cover have accelerated from 2000–2018, relative to the longer satellite record. In addition, although the northern Bering Sea is typically ice covered for 5–6 months annually, there have been dramatic winter sea-ice reductions in 2018 and 2019. Stabeno et al. (2019) show that since 2014 sea ice has arrived later and retreated earlier, resulting in a shorter ice season. They suggest this reduction is related to the delayed arrival of sea ice in the Chukchi Sea since overall, the Chukchi Sea freezes prior to the northern Bering Sea. Sea ice impacts the marine ecosystem in multiple ways: Early retreat of sea ice is correlated with warmer sea surface temperatures in the summer; delayed arrival of sea ice results in warmer bottom temperatures in fall and winter; multiple, consecutive years of extensive ice appear to be related to decreasing salinity and nutrients (specifically nitrate and phosphate), and the timing of ice retreat influences the life cycle of the zooplankton *Calanus* spp. as warmer waters increase copepod development rates. Pickart et al. (2019) present results from 24 hydrographic transects across Barrow Canyon from 2010 to 2013 as part of the DBO effort to evaluate the seasonal development of water masses in the canyon from July–October with periodic upwelling events. During most of these observations, more saline water was found along the eastern flank of the canyon, and occasionally Atlantic Water intrudes into the deepest portions. The Pacific-origin winter water was found at depth, banked against the western flank of the canyon, and was readily found in August. Roughly a third of the 24 hydrographic sections were preceded by up-canyon winds and demonstrate influence from upwelling. During these periods, more saline water was found along the eastern flank of the canyon, and occasionally Atlantic Water intruded into the deepest portions. Okkonen et al. (2019) provide a complementary study by presenting a decade of hydrographic data collected in August 2005–2015 in the Barrow Canyon region of the northern Chukchi Sea. Barrow Canyon is a known conduit through which Pacific-origin waters carrying nutrients, biota, freshwater, and heat into the Arctic Ocean proper. Their findings indicate that Pacific-origin and melt water masses in Barrow Canyon are significantly-correlated with daily sea-ice extent in the eastern Chukchi Sea for most of the May-August ice retreat season. Interannual differences are also shown to be correlated with changes in seasonally-averaged regional winds, as defined by the strength and longitudinal location of the Beaufort Sea high pressure cell.

Data collected prior to the formal initiation of the DBO program, but pertinent to the PAR, were analyzed by three additional papers in the Barrow Canyon (DBO5 region) and one paper in the Beaufort Sea (DBO6 region). Shroyer and Pickart (2019) provide results from ship-based sampling in July-August 2009, along with numerical simulations, to investigate the seasonal transport of Pacific Winter Water to Barrow Canyon. Both the field data and modeling effort identified transit times along the three Chukchi shelf pathways transiting Barrow Canyon – one pathway along the Alaska coast, one pathway south of Hanna Shoal, and one pathway north of Hanna Shoal. These flow paths have a temporal influence on the extent of winter water occupying the canyon. The observations and model indicate that the transition between water types exiting the canyon can occur over time scales of days to weeks, meaning that seasonality within Barrow Canyon is tied to seasonality of the Bering Strait inflow. Pisareva et al. (2019) present time-series results from a mooring deployed from 2002–2004 near the head of Barrow Canyon, along with atmospheric and sea-ice data, to investigate the seasonal signals in the canyon as well as upwelling events. The flow was down-canyon (northeast) for most of the year (except February when up-canyon counter-winds were strongest) and consisted of cold and dense Pacific-origin winter water. Over the two-year study period there were 54 upwelling events, with most events resulting in the re-introduction of Pacific Winter Water back onto the Chukchi Shelf, rather than advection of Atlantic Water. Finally, Lin et al. (2019) evaluated 6 years of mooring data from the Alaskan Beaufort Sea slope, coincident with meteorological observations, to evaluate the occurrence of wind-driven upwelling and associated atmospheric forcing. Easterly winds were strongest over the entire shelf when the shelf-break jet flows to the west, with an eastward-flowing "rebound jet" observed at the end of these events. During a majority of the observed upwelling events, Atlantic Water (AW) rose onto the Beaufort Sea shelf-break, but in some cases only Pacific Water (PW) was upwelled, owing to seasonal variation in the PW-AW interface offshore of the shelf break. These variations were attributed to the differential influence of the two regional atmospheric forcing centers – the Aleutian Low and the Beaufort High.

3. Phytoplankton and Nutrients

There is both a temporal and spatial gradient in water column primary production in the DBO regions: In the recent past DBO1 south of St. Lawrence Island had a phytoplankton bloom in early/mid-May (Cooper et al., 2012); this spring bloom was observed at DBO2 north of St. Lawrence Island in the Chirikov Basin in late May (Cooper et al., 2013), with blooms reaching a maximum at DBO3 in the southeast Chukchi Sea in June/July (Grebmeier et al., 2015a), and in July/August at DBO4 in the northeast Chukchi Sea (Danielson et al., 2017). Giesbrecht et al. (2019) evaluated phytoplankton, nutrient data and productivity measurements over ten years within the five biological 'hotspots' (DBO1–5) in July 2006, 2008 and 2011–2016. Bottom nitrate concentrations over the 10 years were highest in deeper water, and euphotic-zone integrated values were highest in the Chirikov Basin (DBO2). Subsurface chlorophyll *a* maxima occurred at about 30 m depth at most DBO locations during every July cruise. Phytoplankton > 5 μm in size, dominated by diatoms, accounted for ~65 % of total chlorophyll *a* for all regions, except in areas influenced by low-nutrient Alaska Coastal waters on the eastern side of the Chukchi Shelf near the Alaska coast, which were dominated by coccolithophores and small flagellates. Waga et al. (2019) presents data on the spatial and temporal dynamics of phytoplankton size structure in the DBO1 to DBO3 regions. These authors evaluated changes in phytoplankton size structure using satellite color data and field measurements to investigate impacts of the variations on benthic macrofaunal distribution. Their study determined that the flux of organic carbon input to the seafloor was strongly related to surface phytoplankton size structure after the spring bloom. They also found a northward shift in benthic biomass that they suggest was driven by a spatiotemporal change in phytoplankton size structure during the post-bloom period. They concluded that the use of satellite sensing to estimate phytoplankton size structure can be a useful technique for evaluating ecosystem dynamics in the region.

4. Benthos and Fish

The DBO regions in the PAR are anchored by the high productivity of the benthic fauna as they often integrate overlying ecosystem processes that maintain persistent biological hotspots. Goethel et al. (2019) used dynamic factor analysis (DFA) to track underlying trends in the abundance and biomass of a common bivalve, *Macoma calcarea*, at 11 stations in the DBO1 and DBO3 regions. *M. calcarea* abundance and biomass were analyzed from 1998 to 2014 as part of a 25+ year benthic community dataset. Overall the authors concluded that *M. calcarea* abundance and biomass declined in the DBO1 region over that time period, with some spatial complexities including a northward shift of *M. calcarea* abundance. By comparison, abundance of *M. calcarea* in the DBO3 region exhibited a southward shift in abundance away from station UTN5 and towards UTN2, suggesting that hydrographic influences on sediment composition and food supply may be key drivers for this species. Kędra et al. (2019) used the stable nitrogen isotope composition of compound-specific amino acids ($\delta^{15}N_{AA}$) to assess how benthic species are responding to the earlier timing of sea-ice melt and the shift in timing of the onset of the annual production season. Results indicated that the $\delta^{15}N_{AA}$ values of individual species varied geographically, but not necessarily by latitude, with the most positive $\delta^{15}N$ values observed in depositional zones within DBO1. The authors concluded that some benthic species can have high feeding plasticity, particularly with deposit feeding consumers likely adjusting behavior in response to the quality of organic matter reaching the sea floor, thus facilitating the capacity of benthic infauna to shift feeding strategies as an adaption to changes in food quality and supply. Meadows et al. (2019) evaluated current and past benthic systems by comparing molluscan distributions (current sampling) to dead assemblages (shell fragments collected with live samples). The benthic communities in the southern DBO regions area are responding to new pelagic predators, more variability in the type and amount of deposited food, and altered sediment grain size, with macrofaunal dominance shifting from diverse communities of specialized suspension or deposit feeders to facultative deposit feeding guilds. The authors concluded that live-dead discordance in mollusk distributions can thus reliably differentiate between stable and rapidly changing habitats in cold, high-latitude settings. Evaluation of biomass and community composition may be as robust as numerical abundance data, and can improve spatial resolution of past benthic communities in relation to current ones.

Cooper et al. (2019) report on benthic video imagery obtained from past and recent DBO data collections (DBO1–5). Cluster analysis and non-metric multidimensional scaling was used to identify epibenthic assemblage types in relation to sediment characteristics. Video footage from all stations in the DBO 1-5 grid was obtained, and has been made freely available. Quantitative measurements of brittle stars and sea stars showed that density and biomass estimates were comparable within an order of magnitude with existing trawl data. Sandier sediments were observed to have diverse epifaunal communities of filter feeders, while in muddier sediments, deposit feeders such as brittle stars predominated. Iken et al. (2019) evaluated epibenthic invertebrate and demersal fish assemblages at two different spatial scales to help determine appropriate sampling scales. This multivariate analysis effort evaluated the broader spatial coverage undertaken within the Arctic Marine Biodiversity Observing Network (AMBON) program and compared the capacity of that community characterization effort to more limited DBO transect line sampling density in the Chukchi Sea. Overall, the epibenthic and demersal fish diversity in the DBO3 area was well represented by both sampling grids, but comparison of sampling scales in the northern DBO4, led to a conclusion that there is a need for a higher density and extension of offshore sampling on the DBO4 line to accurately characterize epibenthic and demersal fish communities. The authors also suggested sampling every 2–3 years for epibenthic and demersal fish sampling is sufficient to evaluate biological change in those communities.

5. Marine Birds and Mammals

Kuletz et al. (2019) examined seabird distributions in the eastern Pacific Arctic and whether the DBO captures areas of high seabird abundance. The authors used vessel-based survey data within DBO regions 1–8 study areas from July-October during the years 2007–2015. Their work evaluated seabird species richness, diversity, abundance, and community composition, both in the DBO regions as well as broader geographic observations. In general, they found the avifauna of DBO sites are representative of the respective surrounding area, although sampling efforts in the Beaufort Sea were limited. Species richness was highest in the Bering Sea and lowest in the Beaufort Sea. Species diversity indices were similar among DBO sites and regions, except in the more depauperate eastern Beaufort Sea. Total seabird abundance was highest in and near Bering Strait, and dropped abruptly northward and eastward of Point Barrow. The authors concluded that the DBO array captured major hotspots of seabird abundance as well as seabird communities, except for the fulmar-dominated community on the outer Bering Shelf.

Moore and Kuletz (2019) note that marine birds and mammals can act as sentinels to shifts in ocean ecosystems, due to their (i) reliance on finding aggregated prey for efficient foraging, (ii) need to respond to biophysical signals in support of successful seasonal migrations, and (iii) capacity to reflect changes in marine food webs. They present an abbreviated review of recent published accounts of marine bird and mammal responses to biophysical features of the ocean ecosystem in and near sampling regions of the DBO. The review provides both *context* for seabird surveys and marine mammal watches conducted in conjunction with DBO sampling and *support* for the inclusion of marine bird and mammal research, either by direct sampling or collaboration, in the protocols of other ocean observatories. The review is framed by the ocean processes embedded in the Arctic Marine Pulses (AMP) conceptual model (Moore et al., 2018b), goals that include integrating those data in marine ecosystem analyses (see Fig. 3 in their paper).

6. Summary and future directions

This first DBO special issue focuses on the physical forcing and various levels of ecosystem responses, including lower to upper trophic levels, in the PAR. However, there is ongoing interest to further develop the DBO network into a pan-Arctic observation system in coordination with PAG and the Marine Working Group of the International Arctic Science Committee. Understanding biological responses to rapidly changing sea-ice cover and water column properties in the PAR requires collaborative sampling across multiple spatial and temporal scales using both dedicated and opportunistic national and international observational platforms. With the rapid pace of these changes, such as the dramatic lack of sea ice in winter 2018 in the DBO1 region in the northern Bering Sea (Stabeno et al., 2019; Frey et al, 2018; Grebmeier et al., 2018), the DBO is in many ways a flagship example of an Arctic observing system appropriate in scale and approach for the complexities associated with ecosystem responses to climate change.

The DBO program leverages both national and international interests and existing projects to occupy transects for select hydrographic and biological measurements. Continuation of the DBO within the Sustaining Arctic Observing Network activities of the Arctic Council will facilitate further development of the international observing pan-Arctic network. Within the DBO program, the use of a standard DBO parameter file for data archiving is also useful for both nationally and internationally shared data sets that could be an example for future activities. DBO data can also provide a means to test developing conceptual models, such as the AMP conceptual model (Moore and Stabeno, 2015; Moore et al., 2018b). This conceptual model links processes in four previously-defined contiguous ecological domains for the PAR, particularly a pelagic-benthic coupling model (Grebmeier (2012) and references therein) and an advective model (Grebmeier et al. (2015c) and references therein). The standard inclusion of marine bird and mammal surveys in the DBO provides a means to further explore how upper trophic species can act as sentinels to shifts in the PAR ocean ecosystem. This capacity is germane not only to the DBO, but to all ocean observatories. Indeed, the Global Ocean Observing System (GOOS) is now advancing the goal of including data products from research on marine turtles, birds, and mammals as Essential Ocean Variables (EOVs) in the global system of ocean observatories (Miloslavich et al., 2018; www.goosocean.org/eov). Work on this goal is in the early stages, which makes this an opportune time to consider how standard observations of marine birds and mammals in the Pacific Arctic might contribute to this global ocean observation enterprise.

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