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SPECIAL ISSUE ON

THE NEW ARCTIC OCEAN


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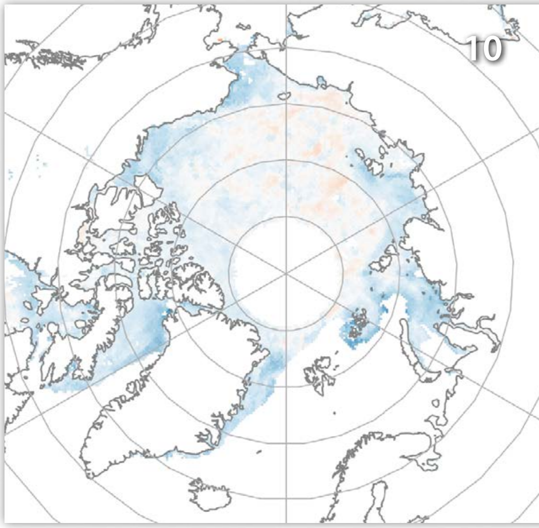
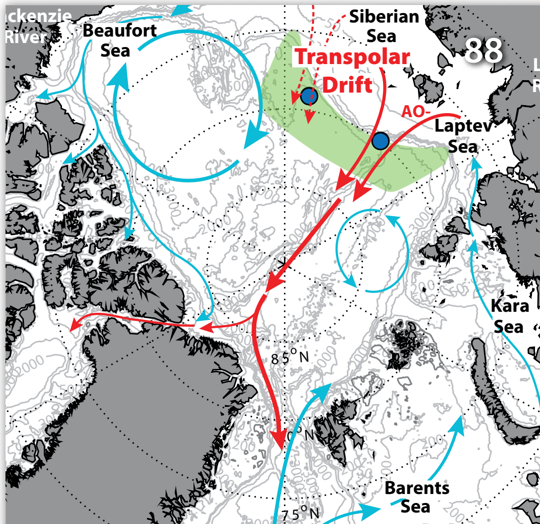
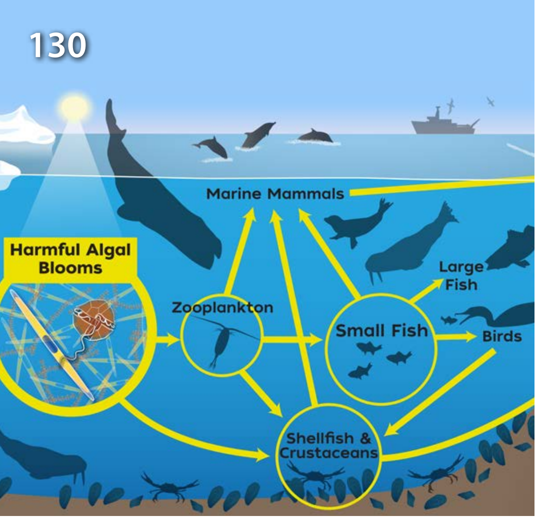
SPECIAL ISSUE ON THE NEW ARCTIC OCEAN



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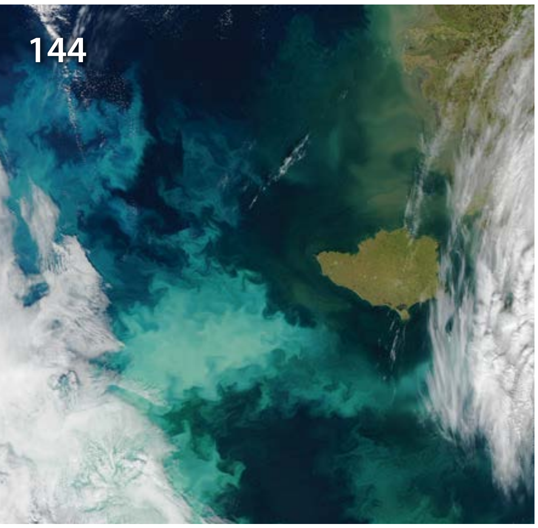
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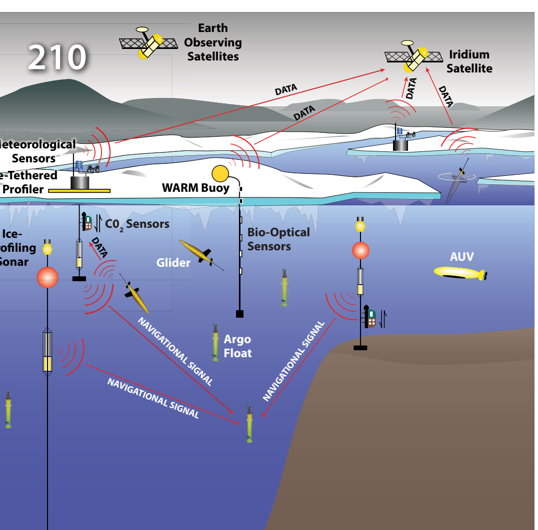
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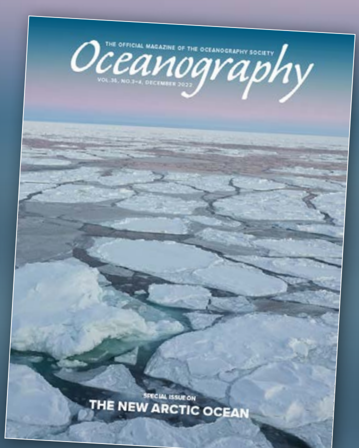
A sunset view of Arctic sea ice freeze-up from R/V *Polarstern* at 11.8°E, 81.5°N on September 29, 2020. The photo was taken during the transit home after the year-long Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. *Photo credit: Melinda Webster, University of Alaska Fairbanks*



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THE ARCTIC OCEAN: ROUND TWO

EVERY DECADE OR SO, it is worth revisiting a topic that we previously covered in *Oceanography* to provide the community with updates on progress. This special issue on The *New* Arctic Ocean is the latest example. In 2011, we published a special issue on The *Changing* Arctic Ocean (https://tos.org/oceanography/issue/volume-24-issue-03) featuring some of the advances made in polar science resulting from the International Polar Year of 2007–2008. Articles in this current special issue further explore the continuing, profound, and increasingly rapid changes occurring in the Arctic Ocean, illuminated by another decade of advances in data collection, analysis, and computation, and enriched by infusions of Indigenous knowledge. Continued warming of the "new" Arctic Ocean, which is already exhibiting further sea ice decline and "Atlantification," more coastal erosion, the potential for more frequent and larger harmful algal blooms, and alterations to ecosystem functioning, among other significant changes, is of great consequence to local coastal communities' food security and infrastructure, and some changes, such as sea ice decline, likely have global implications.

Tom Weingartner led the guest editor team that included Carin Ashjian, Lawson Brigham, Thomas Haine, Liza Mack, Don Perovich, and Benjamin Rabe. All are credited with giving careful consideration to the seven topics covered in this special issue, soliciting article contributions from a wide range of experts who work on Arctic Ocean problems, and shepherding the articles through peer review—much of which was accomplished when the COVID pandemic was still strongly affecting research and teaching. It is perhaps an understatement to say it was a challenging time to publish. In addition to giving the guest editors a shout out for their time, effort, and thoughtful input that led to an outstanding, well-rounded set of papers, I would like to thank the US Arctic Research Commission; the National Science Foundation, Office of Polar Programs, Arctic Sciences Section; and the Office of Naval Research for supporting production of this special issue.

Ellen S. Kappel, Editor

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INTRODUCTION TO THE SPECIAL ISSUE ON

THE NEW ARCTIC OCEAN

By Thomas Weingartner, Carin Ashjian, Lawson Brigham, Thomas Haine, Liza Mack, Don Perovich, and Benjamin Rabe

One hundred and thirty years ago, Fridtjof Nansen, the Norwegian polar explorer and scientist, set off on a bold three-year journey to investigate the unknown Arctic Ocean. The expedition relied on a critical technological development: a small, strong, and maneuverable vessel, powered by sail and an engine, with an endurance of five years for twelve men. His intellectual curiosity and careful observations led to an early glimpse of the Arctic Ocean's circulation and its unique ecosystem. Some of Nansen's findings on sea ice and the penetration of Atlantic Water into the Arctic Ocean established a benchmark against which we have measured profound changes over the past few decades. In contrast, little was known about the Arctic Ocean's ecosystem processes prior to the onset of anthropogenic climate change. Nansen's successes, which paved the way for subsequent research, were gained in part from Indigenous Greenlanders who taught him how to survive in this harsh environment.

A little over a century after Nansen's expedition, the scientific community staged the fourth International Polar Year (IPY) in 2007–2008[1]. That IPY, motivated by the development and persistence of profound changes in the Arctic Ocean's physical environment and its ecosystems over the preceding decades, consisted of extensive international observational efforts and inspired the development of new models, technologies, and novel approaches to entrain the insights of Arctic residents into Arctic studies. The changes that catalyzed the impetus for the IPY included the dramatic shrinking in thickness and extent of summer sea ice, warm pulses of Atlantic water circulating through the Arctic Ocean's sub-basins, an increase in the heat flux from the Pacific to the Arctic, variations in freshwater storage within the Arctic basin, and alterations in the marine ecosystems and biogeochemical cycles of the Arctic Ocean and its adjacent continental shelves. The IPY results generated new questions concerning the internal and external mechanisms that control the Arctic Ocean and its role in global climate, and its evolution toward a new, but uncertain, climatic state. These processes span a broad spectrum of interconnected spatial and temporal scales and entail complex but inadequately known interactions. Increasingly sophisticated climate models predict that warming of the Arctic's atmosphere and ocean will continue, with the Arctic eventually becoming seasonally ice-free. Understanding how the Arctic Ocean will adjust to these changes and their ramifications for society poses challenges that motivate continued national and international scientific efforts. One goal of these studies is to try to determine how the Arctic Ocean will evolve so that accurate predictions can be made to guide socio-economic decisions. To summarize all these advances, *Oceanography* devoted a special issue in 2011 to the IPY (https://tos.org/oceanography/issue/volume-24-issue-03).

Yet, after only one more decade of change in the Arctic Ocean, another special issue is due. This one—The New Arctic Ocean—highlights some of the scientific advances and illuminates the considerable international investments undertaken since the 2007–2008 IPY. The papers comprising this issue summarize the status and current trends of the Arctic Ocean, explore many of the processes and interactions controlling these trends, assess gaps in our understanding, suggest directions for future research, discuss geopolitical topics pertinent to the potential industrial development of the Arctic Ocean, and describe some of the concerns and responses of the Indigenous communities that depend upon this unique marine ecosystem. This special issue is constructed around seven broad, albeit overlapping, research themes that focus on sea ice, physical oceanography (including ocean circulation), pan-Arctic and global perspectives, marine ecosystems and biogeochemistry, geopolitical considerations, Indigenous perspectives, and several recent and ongoing long-term

[1] Previous IPYs occurred in 1881–1884, 1932–1933, and 1957–1958, the latter also called the International Geophysical Year (IGY) because it included research outside the polar areas.



observational efforts and techniques. The presentations include both papers and sidebars (short reports) that highlight some of the research findings, approaches, challenges, and outstanding questions developed over the past decade.

Within the sea ice theme, **Meier and Stroeve** summarize current trends in sea ice concentration, age, and thickness; snow depth; and melt and freeze-up dates using satellite-borne passive microwave sensors, and they consider the factors driving these trends. **Holland and Hunke** provide an overview of current and near-future sea ice models developed for use in climate studies, discuss recent advances for improving sea ice predictability, and examine prediction consistencies across many of these models. **Webster et al.** illustrate the spatial and temporal scales of sea ice variability and discuss how this variability can complicate the synthesis of ice observations from disparate sampling methods. They then discuss how combining observations across spatial and temporal scales can resolve these complications and yield a better understanding of Arctic sea ice system behavior. Two sidebars complement these papers. **Perovich** describes autonomous ice mass balance buoys that collect time-series observations of snow and ice accumulation and melt. He then shows that in collocating these buoys with other autonomous systems, an observational network of the atmosphere, ice, and ocean is achievable. **Kwok** provides an overview of the ICESat-2 altimeter's abilities to observe sea ice and continental ice sheets and to detect the topography of the sea surface height field, which reflects the ocean circulation.

Changing sea ice properties interact with the Arctic Ocean's physical oceanographic regime consisting of water masses, circulation, and mixing. **Rudels and Carmack** discuss how these processes, mediated by winds, the influx of waters from the North Pacific and North Atlantic Oceans, and the enormous circumpolar terrestrial runoff, influence the basin's stratification and the subsequent export of Arctic Ocean waters into the North Atlantic. Along the same vein, a sidebar by **Pnyushkov and Polyakov** details the recent history of changes in North Atlantic-derived waters flowing along the Eurasian continental slope and their connection to lower latitude processes. The extensive continental shelf area of the Arctic Ocean receives a massive riverine sediment load that will increase with climate warming and affect biogeochemical processes. **Kipp and Charette's** sidebar describes how radium isotopes are effective tracers of terrestrial-derived elements and are used to monitor alterations in the Arctic Ocean's chemistry. **Von Appen et al.** review the geographical heterogeneity and importance of mesoscale (~10 km diameter) eddies that influence basin dynamics and much of the mass and material exchanges between the continental shelves and the deep basin. At even smaller scales, **Rippeth and Fine** review turbulent mixing in an increasingly ice-free Arctic Ocean, and then discuss how this mixing varies geographically, and its sensitivity to the changing seasonal ice cycle. **Thomson et al.** focus on the complex air-ice-ocean feedback mechanisms that drive autumn ice formation and discuss the spring and summer preconditioning processes that influence fall freeze-up.

The exchange of waters between the North Atlantic and Arctic Oceans influences the Atlantic Meridional Overturning Circulation (AMOC), which plays an important role in global climate and oceanic sequestration of CO_2. **Weijer et al.** review recent observational and modeling efforts that advance our understanding of the impacts of the changing Arctic Ocean on the AMOC and the effects on the Arctic due to feedbacks from the AMOC. **Bacon et al.** discuss how inverse methods, when applied to long-term measurements collected along the Arctic Ocean's maritime boundaries, can be used to generate estimates of surface fluxes of heat and freshwater, net biogeochemical fluxes, and estimates of ocean water mass transformation rates. The AMOC is also influenced by fresh water discharged from the Greenland Ice Sheet. A sidebar by **Wouters and Sasgen** examines changes in Greenland ice sheet mass from 2002 to the present using data from the Gravity Recovery And Climate Experiment (GRACE) and the GRACE-FollowOn



satellite missions, and discusses the implications of this ice loss for global sea level. In another sidebar, **Briner** compares the current rate of Greenland ice loss to ice losses over the past 12,000 years. **Straneo et al.** describe how this glacial discharge, along with numerous other interacting factors, impacts local coastal ecosystems and Greenland's Indigenous peoples.

The loss of sea ice and changes in its seasonality have profound influences on the Arctic Ocean's ecosystems and biogeochemical cycles, with consequences for the peoples who rely on these ecosystems for their sustenance, culture, and livelihood. **Juranek** discusses how spatially and temporally varying factors within sub-regions of the Arctic give rise to a complex suite of biogeochemical and ecological responses relevant to nutrient cycling, trophic transfers, pelagic-benthic coupling, ocean acidification, and the capacity for biologically mediated air-sea CO_2 exchange. As one example of a regional change, a sidebar by **Frey et al.** shows that primary productivity is declining in Bering Strait due to earlier ice retreat and hence earlier nutrient consumption in the northern Bering Sea, with a consequent reduction in the nutrient supply to the Chukchi Sea. **Stafford et al.** review recent changes in the temporal and spatial distributions of the upper trophic level components of the Pacific Arctic region and the linkages of these changes to alterations in prey fields, the warming atmosphere and ocean, and the decrease in duration and extent of sea ice. In their sidebar, **Kaler and Kuletz** describe how such changes are also manifested in the increasing frequency of seabird die-offs in this region. In another article, **Anderson et al.** warn that the increase in ocean warming and the northward transport of cells from lower latitudes in the Pacific Arctic region is increasing the frequency and size of harmful algal blooms that threaten the food resources of Arctic residents.

Rapid Arctic environmental change requires improved collaboration among scientists and Indigenous populations in observing activities that support adaptation, and in the development of appropriate responses to such changes. **Druckenmiller's** sidebar discusses the National Science Foundation's Navigating the New Arctic (NNA) initiative. The NNA is ushering in a new period of convergent research across a diverse range of societal challenges tied to Arctic warming—in which there is greater emphasis on co-production of knowledge, equity, and holding research and researchers accountable for whether their work is benefiting Arctic Peoples. **Erickson and Mustonen** document some of the concerns, difficulties, and adjustments that Indigenous communities face based on interviews and historical references with residents in Erickson's home village of Unalakleet in the northern Bering Sea. Several sidebars describe efforts to engage Indigenous communities in research and in documenting their culture in response to a changing climate. **Fienup-Riordan** focuses on efforts to record the history and oral traditions of the Yup'ik people of Nelson Island, located on the southeast Bering Sea coast. **Ryan et al.** describe a novel program that provides value to both scientists and the residents of Uummannaq Bay, Greenland, by combining remote sensing, ethnographic data, and community-based monitoring to study changes in landfast sea ice. **Chythlook et al.** discuss networking processes in support of Indigenous-led projects on food security. This is part of the Sustaining Arctic Observing Networks (SAON) program, an international collaboration among scientists, Arctic residents, and government agencies to develop a long-term pan-Arctic observing system that serves societal needs.

The loss of sea ice and the increased duration of the open water season in sectors of the Arctic Ocean allow for a potential increase in marine use by a diversity of users and vessels. Such a development raises concerns about safety and protecting this ocean's ecosystems. **Brigham and Gamble** review strategies for using policy measures developed through an array of organizations to protect the Arctic Ocean into the future. They also provide a guide to the International Maritime Organization Code, a new governance regime that addresses marine safety and environmental protection challenges for ships operating in the Arctic Ocean. A



perspective article by **Brigham** considers some of the interdisciplinary issues that will dictate the potential use of the Arctic Ocean as a major shipping corridor.

Sustained and integrated observations are critical to detecting and understanding how changes in the Arctic Ocean will evolve and the potential risks that these changes pose to ecosystems and humans, both regionally and globally. Moreover, results from long-term observing networks often lead to shorter-duration process studies designed to unravel the specific mechanisms underlying the observed changes. Indeed, it was precisely the decades-long collection of observations indicating pronounced and persistent changes in the Arctic Ocean that catalyzed the many process studies of the 2007–2008 IPY and the subsequent development of observational networks and process studies. **Danielson et al.** provide an example of an observational network in the Bering-Chukchi-Beaufort sector of the Pacific Arctic region that involves contributions from, and the priorities of, regional, national, and international funding agencies, private donors, and communities. **Lee et al.** outline the promises and challenges in developing autonomous vehicles coupled to new sensors that will allow for greater efficiency and flexibility in maintaining Arctic Ocean observational networks. These papers are complemented by several sidebars. **Shupe and Rex** describe the year-long Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition conducted in 2019–2020 in the central Arctic Ocean. MOSAiC collected physical, chemical, and biological data at an unprecedented level of detail to resolve the complex linkages among the atmosphere, the ocean, and sea ice. **Morison et al.** show how a sampling design that combines in situ and remotely sensed data enhances observations of Arctic Ocean hydrography and circulation. **Pulsifer and Lee** discuss some of the challenges and approaches to managing the massive data sets being generated by new sensors, platforms, survey tools, and community-driven monitoring programs. Finally, many of the papers discussed in this issue stem from projects that include educational outreach programs to K–12 students and the public. **Forcucci et al.** describe a novel outreach effort that provides a unique opportunity for students and the public to learn about the history of the exploration of the Arctic Ocean and its circulation with toy wooden boats deployed on sea ice from icebreakers.

Nansen's legacy of careful planning to address critical questions, and patient and sustained observations using appropriate technology and Indigenous knowledge, are the basis of Arctic research today. We hope this special issue provides you with an appreciation of the many facets of research underway in the Arctic Ocean, along with its intellectual and technological challenges, successes, and future promises.

ACKNOWLEDGMENTS

The guest editors thank the authors and peer reviewers for their generous contributions of time and effort, especially given the complications associated with the COVID pandemic. Funding for the publication of this special issue was provided by the US Arctic Research Commission, the US National Science Foundation, and the US Office of Naval Research.

PHOTO CREDITS

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AN UPDATED ASSESSMENT OF THE CHANGING ARCTIC SEA ICE COVER

By Walter N. Meier and Julienne Stroeve

Image credit: Melinda Webster, University of Alaska Fairbanks

ABSTRACT. Sea ice is an essential component of the Arctic climate system. The Arctic sea ice cover has undergone substantial changes in the past 40+ years, including decline in areal extent in all months (strongest during summer), thinning, loss of multiyear ice cover, earlier melt onset and ice retreat, and later freeze-up and ice advance. In the past 10 years, these trends have been further reinforced, though the trends (not statistically significant at $p < 0.05$) in some parameters (e.g., extent) over the past decade are more moderate. Since 2011, observing capabilities have improved significantly, including collection of the first basin-wide routine observations of sea ice freeboard and thickness by radar and laser altimeters (except during summer). In addition, data from a year-long field campaign during 2019–2020 promises to yield a bounty of in situ data that will vastly improve understanding of small-scale processes and the interactions between sea ice, the ocean, and the atmosphere, as well as provide valuable validation data for satellite missions. Sea ice impacts within the Arctic are clear and are already affecting humans as well as flora and fauna. Impacts outside of the Arctic, while garnering much attention, remain unclear. The future of Arctic sea ice is dependent on future CO_2 emissions, but a seasonally ice-free Arctic Ocean is likely in the coming decades. However, year-to-year variability causes considerable uncertainty on exactly when this will happen. The variability is also a challenge for seasonal prediction.

INTRODUCTION

This paper is intended primarily as an update to the previous assessment of Arctic sea ice published a decade ago in *Oceanography* (Perovich et al., 2011). Over that decade, substantial changes in Arctic sea ice have been observed (e.g., Meier et al., 2014; Barber et al., 2017), with declining sea ice cover being one of the clearest indicators of change, along with thinning of the ice cover (Kwok, 2018). Spring melt is occurring earlier and freeze-up is trending later, allowing the ice-ocean system to absorb more solar radiation and increasing the energy input into the Arctic. At this point, it is highly likely that ice-free conditions will emerge in September by the middle of the century (e.g., Notz and SIMIP, 2020). It is only under limited future emissions scenarios that the likelihood of largely sea ice-free conditions during summer can be avoided on a regular basis. The impacts of sea ice loss are myriad within the Arctic: warmer ocean waters, longer fetch, more frequent storms, and increased coastal erosion, along with associated effects on the Arctic ecosystem and human activities in the region. The loss of sea ice also amplifies Arctic warming, impacting Greenland ice mass loss and permafrost thawing. The ramifications of sea ice loss outside the Arctic are uncertain, with conflicting evidence of connections to more extreme weather events in the mid-latitudes.

OBSERVING

Ice Concentration and Sea Ice Extent

A series of satellite-borne passive microwave sensors provides a consistent and nearly complete long-term record of sea ice concentration and extent since November 1978. Sea ice extent (sum of the area with at least 15% concentration) has been a workhorse in assessing the state of the ice cover because of the available long, consistent record. Several time series of extent have been produced from passive microwave brightness temperatures via various empirically derived sea ice concentration algorithms (e.g., Comiso, 1986; Spreen et al., 2008; Lavergne et al., 2019). Here, we use the extent record from the US National Snow and Ice Data Center (NSIDC) Sea Ice Index (Fetterer et al., 2017) derived from NASA Team algorithm concentration fields (Cavalieri et al., 1999); extent here is defined as the total area where concentration is greater than 15%. The concentration product begins in November 1978 (Cavalieri et al., 1996), with the most recent data (for 2021 in this manuscript) augmented by near-real-time processing (Maslanik and Stroeve, 1999).

Sea ice concentration and extent are declining everywhere in the Arctic, with the most pronounced losses in summer occurring within the Beaufort, Chukchi, East Siberian, and Laptev Seas, and the largest ice losses in winter within the Barents Sea and the Sea of Okhotsk. (Figure 1a,b). Much of the concentration trend is due to complete loss of ice (i.e., decline in extent and retreat of the ice edge), but some areas within the ice pack are also trending toward lower concentration. This suggests a less compact ice pack that allows more solar absorption during summer and less resistance to wind and other dynamic forcing.

The sea ice extent trend in September, when the annual minimum occurs, is −12.7% per decade, while winter trends are smaller but still statistically significant ($p < 0.05$) (Figure 1c). Trends for 1979–2021 are negative and statistically significant for all months, with extents since 2005 consistently well below normal, particularly during spring and autumn (Figure 1d). The largest departures from average conditions recently have occurred in October, with the largest negative anomaly being the October 2020 extent that was 3.7 standard deviations below the 1981–2010 mean.

Despite statistically significant negative trends, the overall linear trend is marked by strong interannual and decadal variability. Nevertheless, each decade's sea ice extent has been lower than that of the previous decade. The most recent decade has seen particularly extreme September extents with the record low extent reached in September 2012 (3.39×10^6 km^2), and the second lowest extent occurring in September 2020. Overall, the last 15 years (2007–2021) have the 15 lowest September extents in the 43-year (1979–2021) satellite record. However, the trend has been relatively flat over those years ($-8{,}200 \pm 57{,}400$ km^2 yr^{-1}).

Looking at sea ice extent decade by decade, the variability is evident, with the strongest trend during the 2001–2010 decade and the weakest trend in the past decade, 2011–2020 (Table 1). However, most of the decadal trends are not statistically significant due to the short time period of the data. But change in extent is evidenced by the 2011–2020 decade being nearly 1 × 10^6 km^2 lower than the previous decade and almost 2.5 × 10^6 km^2 below the first complete decade in the record (1981–1990).

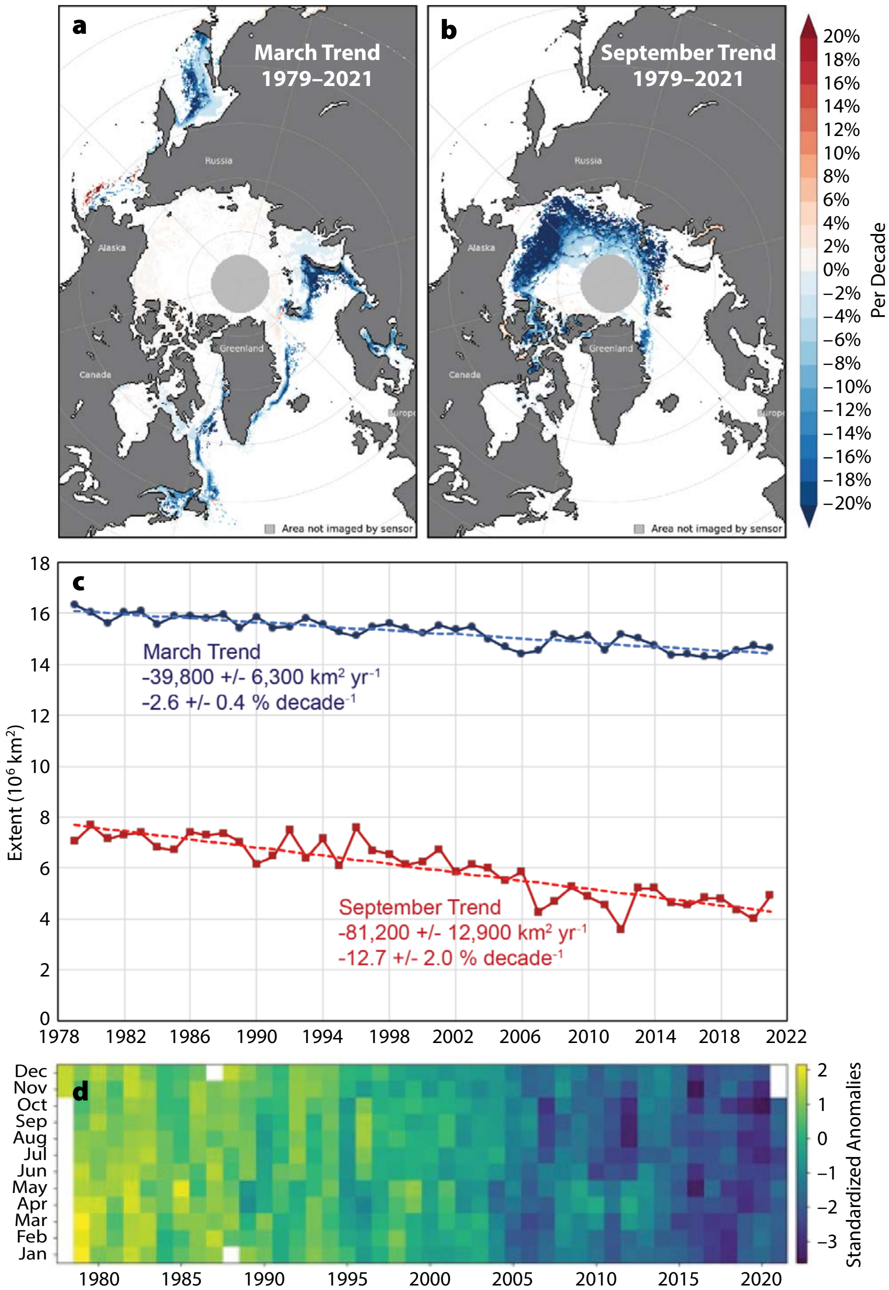

FIGURE 1. Arctic sea ice trends for 1979 to 2021. Percent per decade (relative to the 1981–2010 average) concentration trend for (a) March and (b) September. (c) Percent per decade (also relative to the 1981–2010 average) extent trends for March and September with linear trend lines. (d) Standardized anomalies in Arctic sea ice extent relative to the 1981–2010 long-term average.

TABLE 1. Statistics on September sea ice extent. Trends are given with two standard deviation ranges; significant trends ($p < 0.05$) are in bold. Percent trends are relative to a 30-year (1981–2010) climatological average.

YEAR RANGE	AVERAGE (10^6 km^2)	TREND (10^3 km^2 yr^{-1})	TREND (% $Decade^{-1}$)
1979–2021	5.99	**−81.2 ± 12.9**	**−12.7 ± 2.0**
1981–1990	7.06	−55.6 ± 86.5	−8.5 ± 13.5
1991–2000	6.67	−64.1 ± 118.2	−10.0 ± 18.4
2001–2010	5.51	**−197.9 ± 103.2**	**−30.9 ± 16.1**
2011–2020	4.57	−17.6 ± 117.8	−2.7 ± 18.4

Ice Age

Sea ice age provides yet another long-term indicator of change in the Arctic. Age is tracked via Lagrangian parcels (Tschudi et al., 2020), and a data product (Tschudi et al., 2019a,b) for age is available beginning in 1985. Older, level ice is generally thicker than younger ice (ignoring dynamic thickening), so age provides a general proxy for thickness. Changes in the age distribution within the Arctic indicate a substantial loss of older ice. While multiyear ice (ice that has survived at least one summer melt season) and >4-year-old ice extent have declined almost since the beginning of the record, the last 10 years have seen an almost complete disappearance of ice >4 years old, with extents persistently below 500,000 km^2 since 2012 (Figure 2). The total area of multiyear ice has shown interannual variability since the record low extent in 2012, but it has continuously been well below values seen before 2007. Simply put, sea ice is not remaining in the Arctic as long as it once did.

There are two apparent reasons for this shorter lifetime of ice in the Arctic. One reason is faster ice motion (Kwok et al., 2013). This increase in speed is not explained by increasing wind forcing or currents, but rather it is a greater response to forcing by the younger and thinner ice cover, as well as a less compact ice pack, as noted above in the concentration trend data. This leads to increased area export (Smedsrud et al., 2017), though volume export appears to decrease due to thinning (Spreen et al., 2020). In some respects, this can be thought of as a potential positive feedback mechanism: thinner and less compact ice (due to warming) responds more to forcing and moves faster, exiting the Arctic sooner, which results in a thinner ice cover.

The other aspect leading to less older ice is in situ melting. In particular, in the Beaufort and Chukchi Seas, where ice once circulated clockwise in the Beaufort Gyre, the ice age data show that much of the ice is melting out during summer in that region. This may be due to a combination of warmer ocean waters and a less compact ice pack (which may in turn be due to a thinner, more dynamic ice cover).

Ice Thickness and Snow Depth

While we now have over 43 years of consistent observations of sea ice area and extent, we do not have a similarly long-term data record of sea ice thickness. Thickness, when combined with ice extent or area, provides estimates of ice volume, arguably a more important metric of the overall amount of ice being lost in the Arctic Ocean. Our earliest observations of sea ice thickness were primarily based on submarine upward-looking sonar data collected in the 1980s and 1990s (NSIDC, 1998). In regard to satellite-based approaches, most are based on using radar or laser altimeters. Neither of these technologies actually measure the sea ice thickness, but instead they measure either the radar freeboard, or in the case of laser altimeter, the snow + ice freeboard relative to the water surface. Together with estimates of snow depth, and snow, ice, and water densities, sea ice thickness can then be inferred by assuming the sea ice and its overlying snow cover are in hydrostatic equilibrium (e.g., Laxon et al., 2013). In the case of radar altimetry, a further assumption as to the location of the dominant backscattering surface is needed. This is often assumed to be the snow/ice interface at Ku-band, though this assumption is likely only valid for a cold snow pack over multiyear ice. Altimetric records have higher uncertainties for thinner ice. For thin ice, the use of passive microwave brightness temperatures at L-band have also been used (e.g., Kaleschke et al., 2012), but these estimates are limited to a thickness of about 50 cm, though they can be combined with Ku-band radar altimeter data from ESA's CryoSat-2 mission for an optimal estimate (Ricker et al., 2017).

The first estimates of sea ice thickness for a substantial part of the Arctic (up to 81.5° N) came from the ERS-1 radar altimeter satellite for 1993 to 2001 (Laxon et al., 2003). This was followed by NASA's Ice, Cloud, and land Elevation Satellite (ICESat) laser altimeter mission; however, because of technical problems with the lasers, ICESat only provided snapshots of Arctic sea ice thickness during spring and autumn from 2003 to 2009. Since 2010, CryoSat-2 has provided nearly pan-Arctic observations of ice thickness. Beginning in 2018, NASA's ICESat-2 laser altimeter began providing complementary estimates to CryoSat-2. While these different satellite missions offer glimpses into sea ice thickness variability and change, it remains challenging to blend these data into a consistent

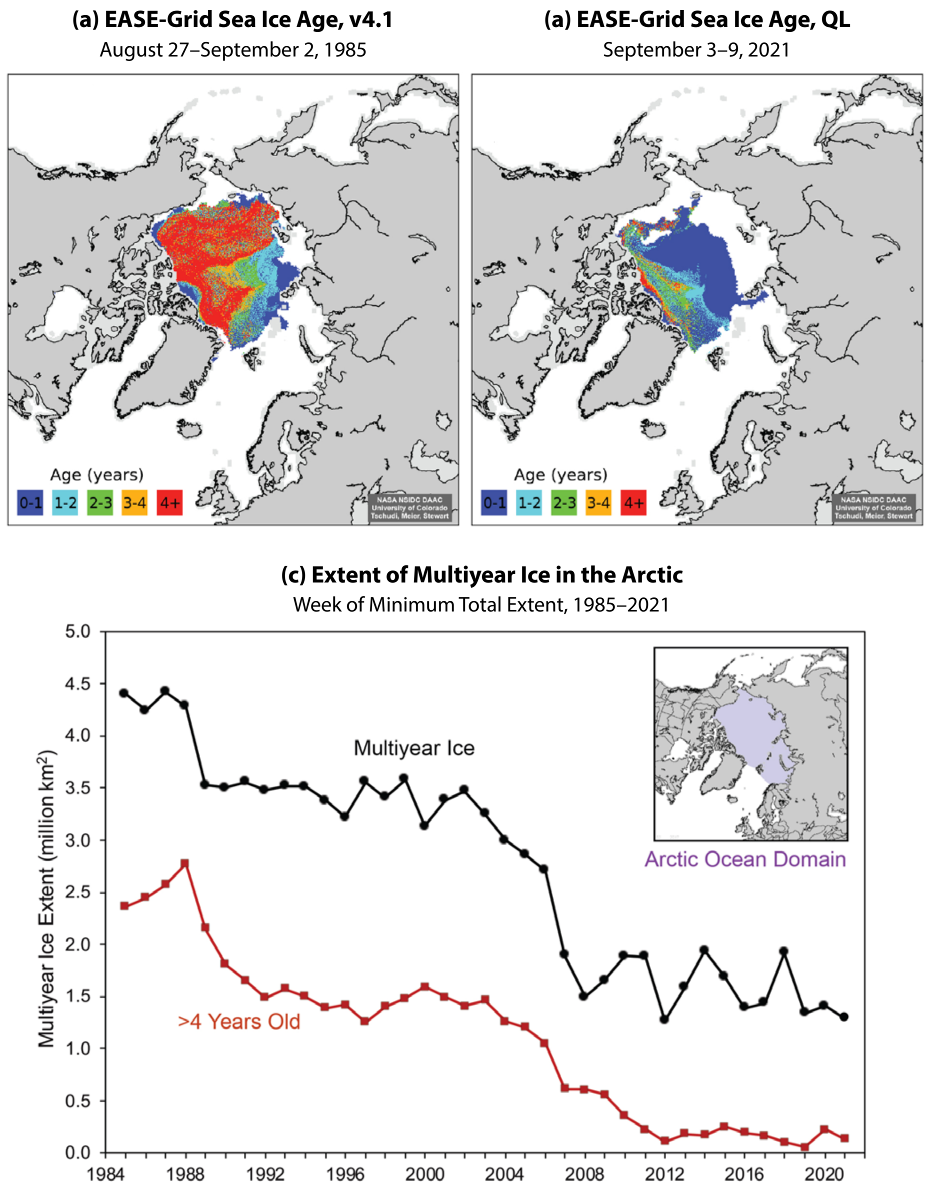

FIGURE 2. Weekly average sea ice age field from the end of summer (week before the annual minimum total extent) for (a) 1985 (from Tschudi et al., 2019a) and (b) 2021 ("QL" = QuickLook version from Tschudi et al., 2019b). (c) Extent of age of multiyear ice (black) and >4 year old ice (red) within the Arctic Ocean domain (inset) for 1985 to 2021. *Figure from Meier et al. (2021)*

record of ice thickness. This in part stems from different sensors (i.e., laser vs. radar altimeter), spatial resolution (i.e., larger footprint of ERS-1 vs. CryoSat-2 generates inconsistencies in the dominant scattering surface observed), differences in assumptions about snow/ice densities, and differences in snow depth estimates used in thickness retrievals. Because snow depth has not yet been accurately observed by satellite, a climatology for snow depth is often applied. Yet, using a climatology can lead to large biases in sea ice thickness trends, especially in the marginal ice zone. There, snow depth is observed to be declining, in part due to later autumn freeze-up and thus less time for the snow to accumulate on the ice (e.g., Stroeve et al., 2020). Figure 3 shows an example of trends in April ice thickness from 2011 to 2020 from the CryoSat-2 data record. In this example, ice thickness retrievals using snow depth and density from Liston et al. (2020) were compared against those using a snow depth and density climatology (e.g., Warren et al., 1999). Conversion of radar freeboard to thickness was based on an algorithm from Landy et al. (2020).

What is clear is that thickness trends are overall larger in magnitude when using a dynamic snow loading data set versus a fixed climatology, and there are some spatial pattern differences in regions with positive or negative thickness trends. However, many regions where the trends are statistically significant at the 95% confidence interval are broadly similar regardless of which snow data set is used. From this we can conclude that during the CryoSat-2 period, end of winter ice thickness is declining most strongly in the Beaufort, Chukchi, East Siberian, Laptev, Lincoln, and East Greenland Seas as well as within the Canadian Arctic Archipelago and Baffin Bay, but thickness is increasing north of the Canadian Arctic Archipelago and in the Barents and Kara Seas (Figure 3).

For a longer-term perspective, Mallett et al. (2021) showed that using a newly developed dynamic snow depth and density product (Liston et al., 2020), ice thickness declined 60%–100% faster between 2002 and 2018 compared to using the Warren et al. (1999) snow depth and density climatology. The most recent synthesis of thickness changes using earlier submarine and mooring data together with measurements from electromagnetic induction sensors on helicopters and aircraft, and airborne and satellite lidar data (Lindsay and Schweiger, 2013) found that between 1975 and 2012, the mean ice thickness declined from 3.59 m to 1.25 m. These ice thickness changes are consistent with the shift from an Arctic Ocean dominated by multiyear ice to one dominated by first-year ice.

As noted above, knowledge of snow depth is essential to retrieve ice thickness from altimetry. Thus, it is useful to briefly comment on progress in monitoring snow depth. The first satellite estimates were based on use of passive microwave brightness temperatures to retrieve snow depth over first-year ice (e.g., Markus et al., 2011). This was later extended to also include multiyear ice (e.g., Rostosky et al., 2018). Another satellite-derived method is based on the assumption that radar backscatter at Ka-band comes from the snow surface, while that from Ku-band comes from the ice surface, and thus the difference between the two provides an estimate of snow depth (e.g., Guerreiro et al., 2016; Lawrence et al., 2018). This has been extended to using a combination of ICESat-2 and CryoSat-2 freeboards (e.g., Kwok et al., 2020). Other approaches attempt to model snow accumulation using atmospheric reanalyses combined with various levels of snow modeling sophistication (e.g., Blanchard-Wrigglesworth et al., 2018; Petty et al., 2018; Liston et al., 2020) in either a Lagrangian or Eulerian framework. The Liston et al. (2020) approach is currently the most sophisticated snow modeling system available for providing physically constrained estimates of snow depth and density. The different approaches provide differing magnitudes in total snow depth and trends, as well as spatial patterns (Zhou et al., 2021). However, most of the reanalysis-based approaches show negative trends in snow accumulation in the marginal ice zone (Figure 4), consistent with later ice formation (see next section). Slight positive trends in snow accumulation are seen north of Greenland and the Canadian Arctic Archipelago, with some data products stretching across the pole (see Zhou et al., 2021).

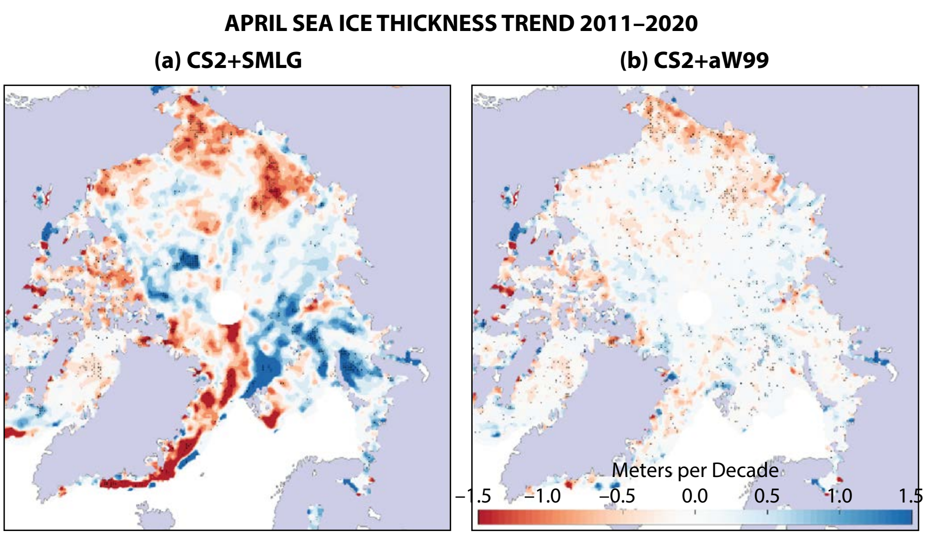

FIGURE 3. Trends in April sea ice thickness in meters per decade between 2011 and 2020 derived from CryoSat-2 (CS2) freeboard retrievals using the Landy et al. (2020) algorithm with (a) SnowModel-LG (SMLG) snow depth and density (Liston et al., 2020) and (b) snow depth and density climatology (adjusted W99; Warren et al., 1999; Laxon et al., 2003). Stippling indicates significance at $p < 0.05$. *Figure provided by J. Landy (University of Bristol)*

Melt Onset and Freeze-up

The sensitivity of microwave emissivity to the presence of liquid water in the snowpack has also allowed for the mapping of changes in the timing of melt onset and freeze-up (e.g., Markus et al., 2009; Bliss and Anderson, 2018; Peng et al., 2018). As expected in a warming Arctic, the melt season is starting earlier than it once did, with the largest changes observed in the marginal seas of the Arctic, with trends on the order of 10–20 days earlier each decade (Figure 5). Slight delays in melt onset occur in the central Arctic (two to five days later each decade). Earlier melt onset has been linked to advection of warm, moist air masses into the Arctic (Kapsch et al., 2013; Mortin et al., 2016).

Trends in autumn freeze-up are in general larger than those of melt onset, with particularly large delays in freeze-up observed in the Beaufort, Chukchi, and East Siberian Seas (up to a month later each decade in the northern Chukchi Sea; Figure 5). Freeze-up is both a measure of when the surface refreezes and also when new ice forms. Despite more modest trends in melt onset compared to freeze-up, earlier melt onset lowers the surface albedo earlier in the melt season, helping to enhance the ice-albedo feedback (e.g., Stroeve et al., 2014). Earlier formation of melt ponds and open water areas results in absorption of more of the sun's energy, in turn fostering more ice melt. The heat gained in the ocean mixed layer as a result of earlier melt onset and earlier ice retreat is strongly linked to the timing of ice formation and thus freeze-up (e.g., Stroeve et al., 2016, 2014).

Finally, earlier melt onset allows for earlier formation of melt ponds, and thus trends toward earlier melt pond formation would be expected. This may be especially important given the role melt ponds may play in the amount of ice left at the end of summer (e.g., Liu et al., 2015). Tracking of melt ponds with satellite data remains challenging given the relatively coarse spatial resolution of satellite data. However, in the past decade substantial progress has been made using optical satellite imagery, such as from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument (e.g., Tschudi et al., 2008; Rösel et al., 2012; Lee et al., 2020), as well as data from the Medium Resolution Imaging Spectrometer (MERIS) satellite (Zege et al., 2015). Data from each has produced melt pond estimates at different spatial and temporal resolutions, making an intercomparison between products difficult. For long-term trends, only Lee et al. (2020) have developed products through 2020, whereas the other products end in 2011 or 2012. Overall, no statistically significant trends toward earlier melt pond development are observed in any of the data products between 2000 and 2011, though Lee et al. (2020) show positive trends during July and August when the record is extended to 2020.

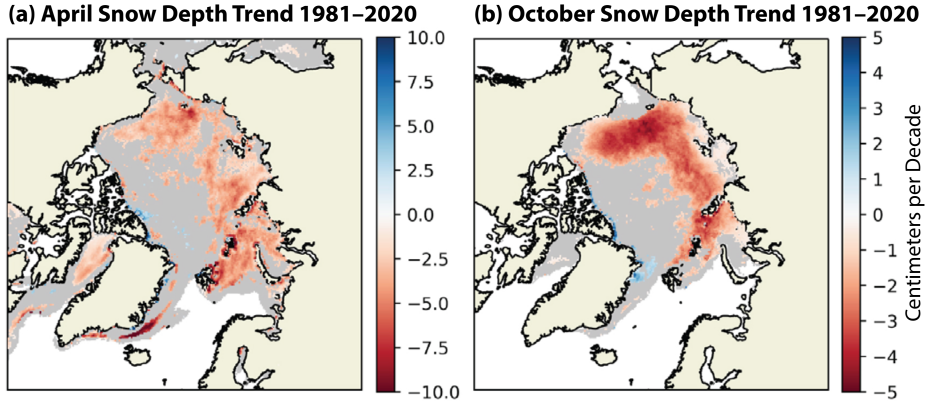

FIGURE 4. Snow depth trends for 1981 to 2020 during (a) spring (April) and (b) autumn (October). Only statistically significant trends (at p <0.05) are shown in color; gray indicates trends that are not significant. *Figure provided by R. Mallett (University College London)*

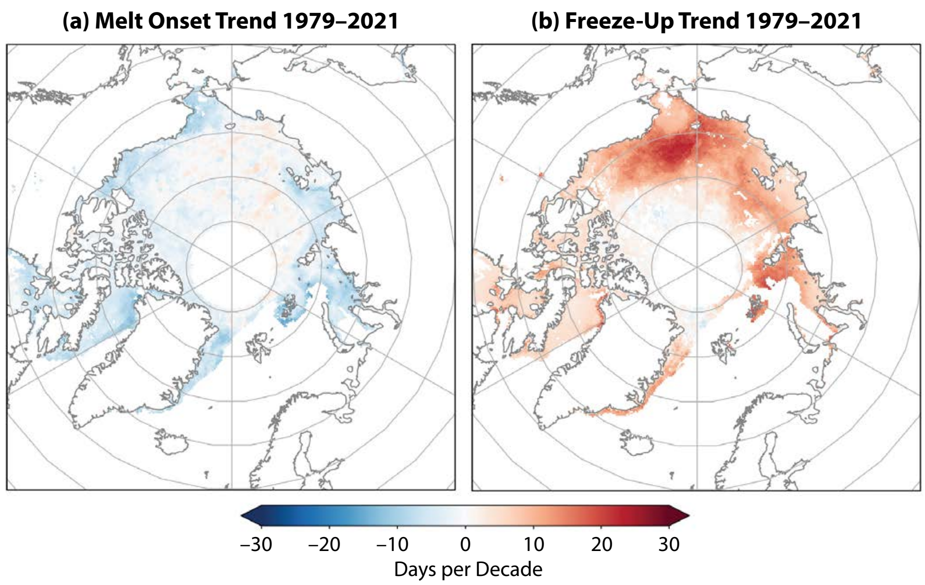

FIGURE 5. Melt onset (a) and freeze-up (b) trends. *Data updated from Markus et al. (2009)*

DRIVERS OF SEA ICE CHANGES

While the overall long-term decline in Arctic sea ice extent is clear (Figure 1), how well a particular year tracks with the linear trend depends strongly on atmospheric circulation patterns (e.g., Parkinson and Comiso, 2013; Ding et al., 2019). Earlier studies show linkages between atmospheric modes of variability, such as the Arctic Oscillation (e.g., Rigor et al., 2002), and summer sea ice extent. However, in recent years, low summer extents have continued regardless of the atmospheric mode. One reason for this is that today's Arctic ice is considerably thinner than it was four decades ago. Higher temperatures and a thinner ice cover serve to precondition the ice cover to be more sensitive to seasonal weather patterns (e.g., Babb et al., 2015). Thus, an unusually warm summer (e.g., Stroeve et al., 2008), or a strong cyclone (Parkinson and Comiso, 2013), can result in large reductions in both volume and extent regardless of the atmospheric mode. Conversely, a colder than average summer may reduce ice melt and permit a relatively thin ice cover to survive.

Another factor in sea ice change is warming of the ocean, which also acts as a positive sea ice-albedo feedback: loss of ice results in more solar absorption in the ocean and warming of the water, which melts more ice (e.g., Perovich et al., 2007). One study found a fivefold increase in summer solar heat absorption in the northern Chukchi Sea between 1987 and 2017 (Timmermans et al., 2018). There is also evidence in the Eurasian Basin that the halocline between the colder, fresher surface waters and the warmer, saltier Atlantic Water below is weakening and contributing to sea ice loss in the region (e.g., Polyakov et al., 2017, 2020; Ricker et al., 2021). Earlier snow melt onset and melt pond formation are also part of a positive feedback mechanism, as they decrease surface albedo and increase solar absorption by the ice (e.g., Perovich et al., 2007).

The variability in forcing and the changing Arctic sea ice response to that forcing make seasonal forecasting challenging. Forecasts of September sea ice with one- to three-month lead times have shown varying but limited skill (e.g., Blanchard-Wrigglesworth et al., 2015; Hamilton and Stroeve, 2016). Forecasting may be becoming more difficult with the thinner ice cover. When the Arctic Ocean was covered by thick ice, an unusually warm summer may have melted a relatively large volume of ice, but this would not have been reflected in a change in extent to the degree that it would be now.

There is still much to learn about the complex processes of the sea ice cover and their interactions with the ocean and atmosphere. While satellite data have greatly expanded our knowledge of these processes, field observations are still essential to validate satellite data and models and to better understand small-scale processes. One of the most momentous undertakings in the history of Arctic science occurred in the past decade: the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC; Shupe et al., 2020). The German icebreaker *Polarstern* was frozen into the ice and drifted across the Arctic from October 2019 to September 2020, collecting ice, ocean, atmosphere, and biogeochemistry data through a full annual cycle. The data are still being processed and substantial results have yet to be reported. But the data collected promise to be a treasure trove for future understanding of the changing Arctic sea ice.

Though details of sea ice processes and interactions with the ocean and atmosphere are still not completely understood, the shrinking and thinning of Arctic sea ice has a clear fingerprint from rising concentrations of atmospheric greenhouse gases. Notz and Stroeve (2016) examined the linear relationship between September sea ice decline and cumulative CO_2 concentrations. When this evaluation was expanded to all months of the year, it indicated that all calendar months demonstrate a clear linear relationship, though the relationship is strongest in September. Updating this analysis through 2021 shows that the linear relationship still holds today (Figure 6). Thus, the long-term fate of sea ice will be determined by which emission scenario (denoted in the IPCC AR6 Report as Shared Socioeconomic

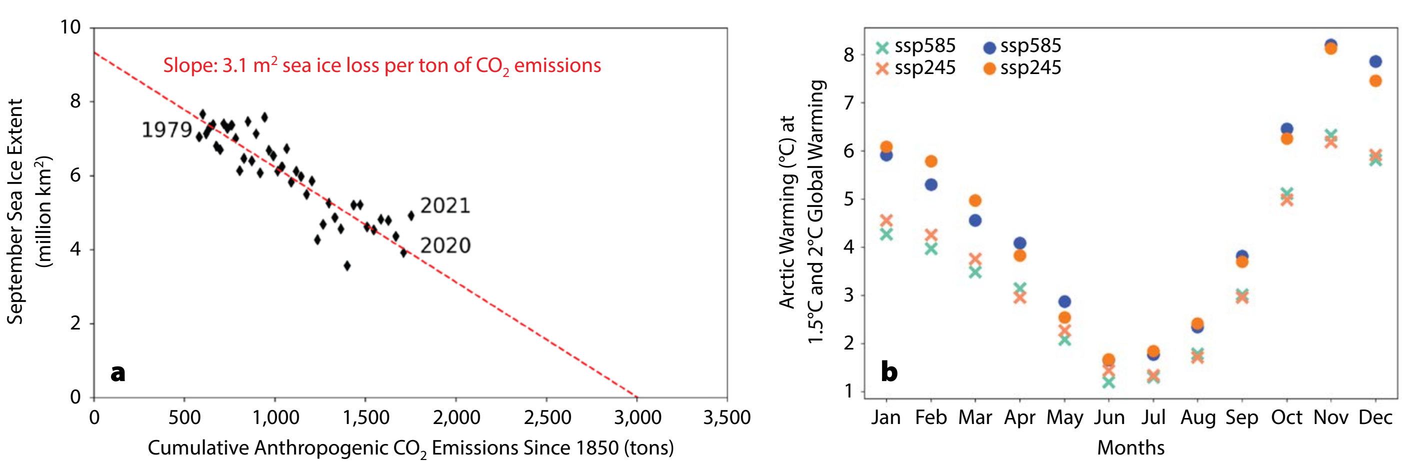

FIGURE 6. (a) September sea ice extent versus cumulative CO_2 emissions for 1979 to 2021 and linear slope. (b) Monthly mean Arctic warming under two future emission scenarios from the latest round of climate model simulations, denoted in the IPCC AR6 Report as Shared Socioeconomic Pathway (SSP) 245 (orange) and SSP 585 (blue) under an annual global warming of 1.5°C (x's) and 2.0°C (circles). *Figure 6a updated from Notz and Stroeve (2016); Figure 6b provided by M. McCrystal (University of Manitoba)*

Pathways [SSPs]) is realized within Earth's climate in the coming decades. Although the target for limiting global warming is 1.5°C, the warming in the Arctic will greatly exceed this amount, with warming as large as 6°C in autumn and winter. If the planet warms to 2.0°C, the warming will exceed 8°C in the Arctic (Figure 6b).

IMPACTS OF CHANGES

The loss of sea ice has myriad impacts within the Arctic. A comprehensive assessment of such impacts is beyond the scope of this paper, but they are detailed in various assessment reports (e.g., AMAP, 2017) and other studies (e.g., Post et al., 2019). Here, we provide brief examples of some of the impacts.

Less sea ice has led to longer fetch, more coastal wave action, and, coupled with permafrost thaw, more coastal erosion (e.g., Overeem et al., 2011; Fritz et al., 2017), results that threaten Indigenous communities and other human infrastructure in the north. Earlier retreat and later advance of ice is opening up shipping routes, and as sea ice declines further, shipping through the Arctic will become more viable in the future (Mudryk et al., 2021).

The loss of ice has fostered earlier and more widespread phytoplankton blooms (e.g., Hill et al., 2018). Double blooms (Ardyna et al., 2014), as well as large under-ice blooms (Arrigo et al., 2012), have been observed in recent years. A lack of ice during Bering Sea winters resulted in substantial effects on the regional ecosystem, including seabird die-offs (e.g., Duffy-Anderson et al., 2019). There are also well-known negative impacts on the megafauna of the Arctic, such as polar bears (Pagano and Williams, 2021), although habitats are expanding for non-ice species, such as killer whales and some fishes (Stafford et al., 2022, in this issue).

While the impacts within the Arctic are clearly visible, the influence of sea ice and Arctic change outside of the Arctic is far more uncertain. Francis and Vavrus (2012) first proposed a connection between Arctic sea ice loss and warming and mid-latitude weather extremes via a slowing jet stream. Their analysis indicated a detectable change in the jet stream pattern that they related to the warming and sea ice loss. However, almost immediately, other studies found contradictory results (e.g., Barnes, 2013). Since then, myriad studies have provided contradictory information. Synthesis studies have tried to reconcile the conflicting research (e.g., Overland et al., 2016), but the debate continues, with studies both supporting (e.g., Cohen et al., 2021) and contradicting (Blackport and Screen, 2021) the hypothesis.

SUMMARY

It is difficult to produce an assessment of Arctic sea ice because changes are happening so rapidly—this document will likely be out of date shortly after publication. In some ways, the story is the same as in the previous report published in *Oceanography* (Perovich, 2011): the rapidly changing Arctic is marked by sea ice loss. On the other hand, substantial developments have emerged in the past 10 years. There was a new record low September ice extent in 2012 and several other extreme low years since then. The oldest ice, already in steep decline 10 years ago, has virtually disappeared and shows no signs of recovery. Since 2011, there have also been substantial new observing capabilities, particularly from altimeters, providing the most complete satellite estimates of freeboard and thickness ever, though there remains important uncertainty in the retrievals (particularly due to snow properties). The Arctic sea ice is showing a consistent response to warming across the myriad observations: decreases in concentration and extent, a younger and thinner ice cover, earlier melt, and later freeze-up.

New projections of sea ice cover confirm an ultimate dependence on future emissions scenarios, though considerable uncertainty will continue in year-to-year variability. Extending the still relatively short records of observations of ice thickness and snow depth and reducing uncertainties in their estimates will help constrain model projections. And future improvements in models (e.g., parameterizations, vertical/horizontal resolution) should also yield more precise projections. A controversial line of research has emerged in the last 10 years, positing a connection between Arctic warming and sea ice loss and mid-latitude weather extremes. Despite numerous studies, the connection remains uncertain and debated within the scientific community. More data, particularly on weather extremes, and improved modeling may help to resolve this question in the future.

What is certain is the impact of sea ice loss within the Arctic. Even 10 years ago, the impacts of sea ice loss on the regional climate, local communities, and the ecosystem were clear and have become only more so since then.

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A REVIEW OF ARCTIC SEA ICE CLIMATE PREDICTABILITY IN LARGE-SCALE EARTH SYSTEM MODELS

By Marika M. Holland and Elizabeth C. Hunke

ABSTRACT. We provide a high-level review of sea ice models used for climate studies and of the recent advances made with these models to understand sea ice predictability. Models currently in use for the Coupled Model Intercomparison Project and new developments coming online that will enable enhanced predictions are discussed. Previous work indicates that seasonal sea ice can be predicted based on mechanisms associated with long-lived ice thickness or ocean heat anomalies. On longer timescales, internal climate variability is an important source of uncertainty, although anthropogenic forcing is sizable, and studies suggest that anthropogenic signals have already emerged from internal climate noise. Using new analysis from the Multi-Model Large Ensemble, we show that while models differ in the magnitude and timing of predictable signals, many ice predictability characteristics are robust across multiple models. This includes the reemergence of predictable seasonal signals in ice area and the sizable uncertainty in predictions of ice-free Arctic timing associated with internal variability.

INTRODUCTION

On average, 25 million square kilometers of sea ice float on the world's high-latitude oceans. Sea ice is frozen ocean—a complicated, dynamic, semisolid mixture of ice, water, salt, and gases. Although sea ice is found primarily in the polar regions, it strongly influences the weather and climate of the entire Earth and has a profound impact on the industries, wildlife, and people who contend with it year-round.

Sea ice forms as seawater freezes, becoming a floating barrier between the air and ocean that reflects solar radiation and impedes transfers of heat and mass. The Arctic climate is changing quickly with September Arctic ice extent declining by over 13% per decade since 1979 (e.g., Serreze and Stroeve, 2015). Climate models predict that September Arctic ice-free conditions are likely by mid-century (e.g., Jahn, 2018). The ice volume is critical for the resiliency of the ice pack under changing environmental conditions; predictions of future sea ice change depend in part on the simulated late twentieth century ice thickness (Massonnet et al., 2018). Ice thickness determines the sensitivity of the ice to melting and freezing, and the area covered by ice increases planetary albedo, the reflection of radiation back to space.

Because of large-scale ice loss, there is growing interest in safe Arctic marine access and a need for reliable predictions on seasonal to interannual timescales. Predictions on multi-decadal scales are also needed for infrastructure planning and to inform climate mitigation and adaptation measures. Earth system model studies have provided new insights on sea ice predictability across timescales. A better understanding of predictability, or the characteristics that enable prediction, provides useful information for building more skillful forecast systems.

Predictability arises from two distinct factors. On shorter timescales, the initial state of the system and dynamics that retain some "memory" of that initial state are sources of predictability. For atmospheric weather forecasts, this "initial-value predictability" enables skillful operational forecasts for about a week (e.g., Krishnamurthy, 2019). For slower evolving components of the system, including the ocean and sea ice, it can enable forecasts on seasonal to interannual timescales (e.g., Blanchard-Wrigglesworth et al., 2011a). Another source of predictability resides in climate drivers, such as rising greenhouse gas concentrations, which elicit a predictable response in the Earth system (e.g., Manabe and Stouffer, 1980). This "boundary forced predictability" enables projections of Arctic sea ice loss on decadal timescales (e.g., Blanchard-Wrigglesworth et al., 2011b) and the predictable transition to ice-free Arctic summers (e.g., Jahn et al., 2016) in response to future scenarios of rising greenhouse gases.

Modeling coupled interactions of sea ice with the atmosphere, the ocean, and nearshore topography are critical for reliable predictions across timescales. Predictions of sea ice properties, such as landfast ice and wave-ice interactions, have required new ice model developments. During the last decade, such developments have led to improved representation of coupled interactions and enhanced realism of the simulated sea ice itself.

In the next section we discuss sea ice models used for climate applications and then advances that have been made with those models for understanding and predicting Arctic sea ice variability and change. In the last section, we outline new developments that are coming online and their implications for sea ice predictive capabilities.

SEA ICE MODELS USED FOR CLIMATE APPLICATIONS

Sea ice is a mixture of open water, thin first-year ice, thicker multiyear ice, and thick pressure ridges. A complex combination of thermal, radiative, kinematic, and mechanical processes determines the composition, structure, and volume of sea ice. Climate simulations require a conservative, consistent, physically accurate representation of sea ice's interactions with the ocean and atmosphere. For models in the recent Coupled Model Intercomparison Project (CMIP; Eyring et al., 2016), the sea ice component consists of a momentum and rheology model for ice motion, a transport model that conserves ice volume and other quantities as the ice deforms and moves, and vertical physics including mechanical and thermodynamic models to compute ice thickness evolution. Keen et al. (2021) summarize the sea ice options used within CMIP6. Newer sea ice models incorporate biology, chemistry, landfast ice, wave-ice interactions, and advanced snow properties, although these developments are not yet routinely used in climate simulations.

Arguably, the most critical sea ice role in the climate system is thermodynamic: snow-covered ice is among the most reflective natural materials, and ice and its overlying snow cover effectively insulate the atmosphere from the ocean. Heat conduction through the ice and snow affects the surface heat flux and determines phase changes throughout the ice (e.g., Maykut and Untersteiner, 1971). Heat tends to flow upward, from the warm ocean toward the colder atmosphere, so sea ice thermodynamics can be represented within a vertical column. Total freezing or melting is computed based on ice-ocean and ice-atmosphere heat exchange, vertically resolved temperatures, and resulting vertical heat conduction.

Representing hydrologic properties, such as liquid water on top of and within the ice, is critical for accurately simulating ice pack evolution. Most CMIP6 sea ice model components employ a basic heat conduction model for the snow, incorporating melt and associated albedo changes along with more complex processes such as snow-ice formation due to flooding and snow infiltration by meltwater, which may form melt ponds. New snow model developments such as wind-driven compaction and drifting of snow into the ocean are now being adopted in climate models (e.g., Lecomte et al., 2013).

For climate-scale simulations, which have spatial resolutions of tens to hundreds of kilometers, many processes require sub-gridscale resolution for improved fidelity. This is captured via an ice thickness distribution (ITD), which computes the horizontal area covered by a given range of ice thickness within a grid cell (e.g., Thorndike et al., 1975). Thermodynamic quantities, including ice growth/melt rates and surface fluxes, are computed for each thickness category. Dynamic properties are also a function of the ITD; for example, ice strength can be modeled as a simple function of ice thickness and concentration (Hibler, 1979), or through an energy-based description tied to the ITD (Thorndike et al., 1975). Inclusion of an ITD influences coupled climate feedbacks (Holland et al., 2006) with implications for climate prediction.

Sea ice surface albedo is computed based on the surface fractions of snow, melt ponds, and bare ice. Because reflectivity differs considerably for these surfaces (Perovich et al., 2002), the relative fractional surface types and how they vary over time affects the surface albedo feedback (Holland and Landrum, 2015). Ice-atmosphere fluxes change the surface characteristics (e.g., melting snow pools into ponds), which then alter the albedo and fluxes. Hydrologic changes also occur. While some models use an empirical relationship between sea ice albedo and ice thickness and surface temperatures, other models apply inherent optical properties to calculate the complex scattering of light within the ice and snow, and the resulting albedos (Briegleb and Light, 2007). Absorbed radiation also induces hydrologic changes, and "mushy" thermodynamic approaches treating sea ice as a two-phase material of brine and ice have been introduced into models (e.g., Vancoppenolle et al., 2009; Turner and Hunke, 2015).

The simplest parameterization of melt ponds empirically adjusts the surface albedo based on the modeled surface temperature and snow depth. More complex, explicit parameterizations (Flocco et al., 2012; Hunke et al., 2013) carry volume and area of meltwater pools on the ice, sourced from ice melt, snow melt, and rainfall. Snow may shield a pond from solar radiation, resulting in radiatively "effective" pond properties used for the shortwave radiation calculation.

Ice velocity is determined by wind, ocean currents, sea surface slope, Coriolis force, contact with land surfaces, and a constitutive model that represents ice strength and rheology. Cracks and ridges in the ice form due to velocity-derived deformation, allowing the direct flux of moisture and heat between the ocean and the atmosphere. Many CMIP6 models use the elastic-viscous-plastic (EVP) rheology (Hunke and Dukowicz, 1997), which introduced an elastic term into the viscous-plastic (VP; Hibler, 1979) ice constitutive equation for computational efficiency. Efficient, monotone, and accurate schemes advect multiple tracers with the ice (Lipscomb and Hunke, 2004).

Neither the model capabilities outlined in this section nor their references are exhaustive here. Newer model developments likely to be incorporated in future climate modeling studies (see later section on Sea Ice Model Advances) are partly driven by the need to better understand the predictability properties of sea ice in climate-scale simulations.

USING MODELS TO PREDICT ARCTIC SEA ICE

Sea ice components have been coupled within Earth system models to enable climate studies. These models freely evolve based on internal dynamics and coupled interactions and prescribe climate drivers such as changes in greenhouse gas concentrations (GHGs) or volcanic emissions. Coordinated experiments (e.g., Eyring et al., 2016), and large ensembles from individual models (e.g., Deser et al., 2020) have resulted in a deeper understanding of sea ice predictability and change. Although structural model uncertainty remains important, many findings are robust across models. In this section we discuss how Earth system models have enhanced our understanding of sea ice and its predictability. We explore some of these factors using results from the multi-model large ensemble (MMLE; Deser et al., 2020; Table 1).

Historical Sea Ice Loss

Climate variations result from external climate drivers ("forced change") arising from both natural and anthropogenic factors, and from internal dynamics ("internal variability") associated with the chaotic system. Simulations that prescribe specific time-varying climate drivers, for example, only GHGs or only natural drivers such as volcanic emissions, indicate that anthropogenic GHGs have played a significant role in historical Arctic ice loss (e.g., Min et al., 2008), with cooling from anthropogenic aerosols offsetting the ice decline by about 23% (Mueller et al., 2018).

In large ensembles of simulations with individual CMIP-class models, differences between ensemble members reflect simulated internal variability. These ensembles have clarified the sizable role of internal variability in many climate properties. For Arctic sea ice, internal variability has a large influence on multi-decadal trends (e.g., Swart et al., 2015), a consistent result across models. Studies suggest that internal variability has reinforced anthropogenic September Arctic ice loss since 1979. For example, by assuming that the mean change from a single model ensemble is a realistic forced response, Kay et al. (2011) found that internal variability accounted for ~50% of the observed 1979–2005 September ice loss.

A robust quantification of the role of internal variability in observed trends is difficult given potential model biases. Comparing large ensembles from multiple models illustrates this challenge. In Figure 1, the fraction of observed ice loss associated with internal variability in the MMLE assumes that an individual model's ensemble mean realistically simulates the externally forced trend. Five of six models suggest that summer ice loss has been enhanced by internal variability, although the magnitude varies. For the remainder of the year, most models also suggest that internal variability has reinforced sea ice loss, although two models (CanESM2 and GFDL-CM3) consistently suggest that internal variability has counteracted forced loss for these months. Notably, for GFDL-CM3 in all months except June–August and CSIRO-Mk3-6-0 for July–October, the ensemble distribution of ice loss is not consistent with observations.

These attribution disparities are related to differences in mean ice area and thickness, which could allow for some observational constraints on the attribution. Alternatively, assessing simulated mechanisms of internal variability and comparing these to observations provides a mechanistic approach. For example, Ding et al. (2019) diagnosed "fingerprints" of internal historical ice loss variability and found enhanced loss in simulations with increasing Arctic atmospheric pressure. The atmospheric circulation variability strongly corresponds with observed changes, estimated to contribute 40%–50% of the observed 1979–2015 summer ice loss. A similar

TABLE 1. The models used in the multi-model large ensemble (MMLE).

MODEL	NUMBER OF MEMBERS	REFERENCE
CanESM2	50	Kirchmeier-Young et al., 2017
CESM1-CAM5	40	Kay et al., 2015
CSIRO-Mk3-6-0	30	S. Jeffrey et al., 2013
GFDL-CM3	20	Sun et al., 2018
GFDL-ESM2M	30	Rodgers et al., 2015
MPI-ESM	100	Maher et al., 2019

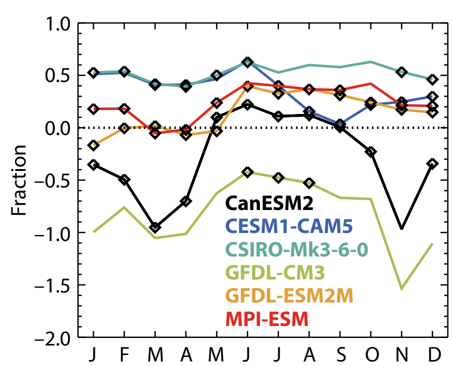

FIGURE 1. The fraction of 1979–2018 observed ice area loss attributed to internal variability from multi-model large ensemble (MMLE) results. Diamonds indicate months when the envelope of the model ensemble spread in 1979–2018 trends encompass the observed trend. Assuming enough members to characterize internal variability, this is a minimum requirement that simulated trends are consistent with observations.

relationship between Beaufort Sea atmospheric pressure and Arctic ice cover emerged from a perturbed-parameter climate model ensemble (Urrego-Blanco et al., 2019). Roach and Blanchard-Wrigglesworth (2022), using experiments in which winds were nudged to observations, also found that observed wind variations reinforced summer ice loss, but played little role in historical winter/spring sea ice trends.

Initial-Value Sea Ice Prediction

Because of sea ice loss, there is growing interest in safe Arctic marine access, and this has spurred interest in predicting sea ice across timescales from seasonal to multi-decadal (e.g., Eicken, 2013; Melia et al., 2017). Earth system models have provided insights on sea ice predictability associated with initial conditions ("initial-value predictability"), including analysis of diagnostic predictability from the correlation structure of simulated conditions, inherent predictability from "perfect model" studies that assess the ability of the model to predict itself, and studies with forecasting systems initialized with observed conditions. There is strong evidence of the potential for skillful seasonal ice predictions and consistency on the fundamental sources of that predictability. These insights are informing the development of improved prediction systems.

Blanchard-Wrigglesworth et al. (2011a) assessed the autocorrelation of Arctic ice extent from a large ensemble and provided a metric for diagnostic predictability. They found that ice anomalies exhibit a persistence of several months and a "reemergence" of memory for some times of year. This includes (1) a summer-to-summer reemergence associated with long-lived ice thickness anomalies, and (2) a melt-to-freeze season reemergence associated with long-lived ocean heat content anomalies. These sources of memory have been confirmed in additional studies (e.g., see Guemas et al., 2016, for a review). They should enable predictive skill on these timescales, while pointing to aspects of the system that need to be well-initialized to realize that skill.

In the MMLE (Figure 2), we find that all models exhibit these predictability features, with a two- to three-month "persistence timescale" over which the autocorrelation declines. For ice area in February through May (y-axis), relatively low correlations after two to three months are followed by an increase in correlation during the ice growth season (approximately January–March, x-axis), indicating the melt-to-freeze season reemergence. Correlations for summer months (August–October) exhibit a summer-to-summer reemergence with enhanced correlations at a one-year lag. While the consistency across the models in these and other properties has been highlighted in several studies, the models differ in the magnitude and timing of predictable signals, which are related in part to different climate state properties (e.g., Day et al., 2014b), providing optimization opportunities for sea ice prediction.

Comparisons across models indicate that climate properties can affect ice predictability—not surprising since the mean ice state influences sea ice feedbacks (e.g., Massonnet et al. 2018)—and suggest that initial-value predictability might change in a warming climate. Indeed, Holland et al. (2019) found that summer ice predictability changes as the climate warms, because the growth of ice thickness initialization errors and their role in summer melt-out depend

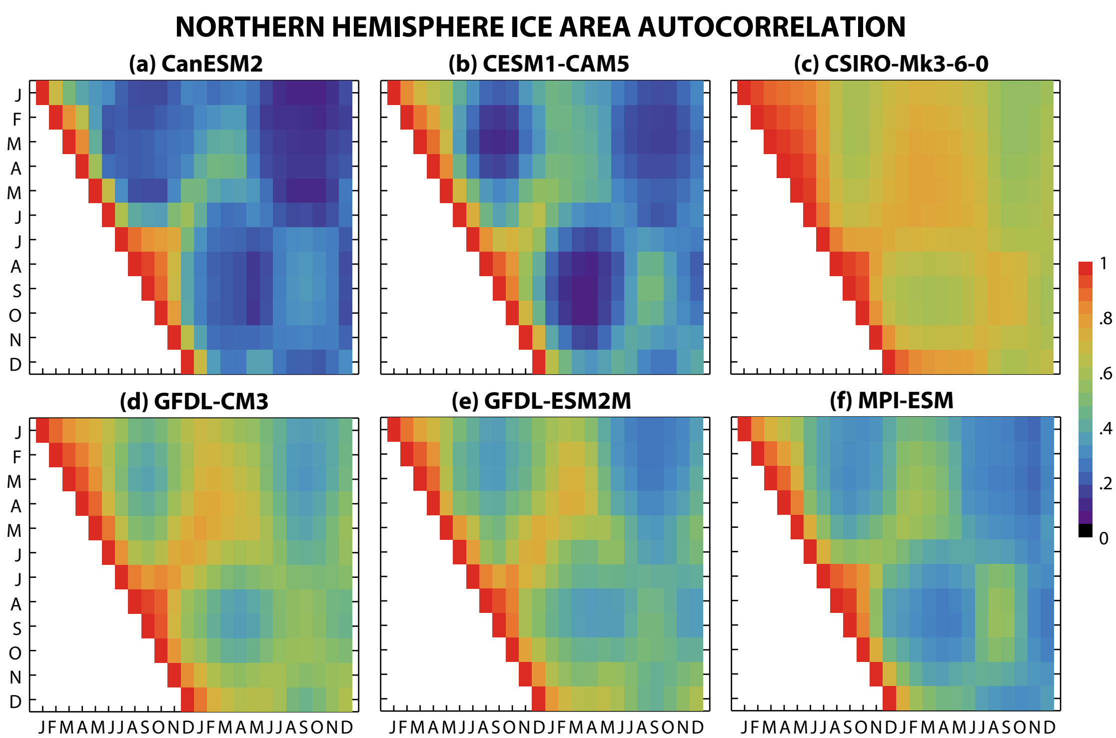

FIGURE 2. Autocorrelation of Northern Hemisphere ice area anomalies from MMLE models using data from 1960–2000 and all ensemble members. Ice anomalies on the y-axis month are correlated with future anomalies shown on the x-axis. To isolate anomalies from internal variability, the ensemble mean is removed from each model.

on the mean sea ice state. These factors can help explain across-model differences in predictability.

Idealized studies indicate that skillful seasonal predictions of ice area should be possible for both pan-Arctic and regional domains. Forecasting systems initialized with observations have been developed to realize this predictability (e.g., Hunke et al., 2020) and exhibit skill in retrospective, seasonal predictions (e.g., Guemas et al. 2016). These systems are also being used to inform data assimilation needs. For example, Bushuk et al. (2019) assessed the importance of different initial conditions for Barents Sea ice predictions by removing certain assimilated observations. They found that sea surface temperatures were important for predictions on interannual timescales, and deeper ocean temperatures played an important role in predicted trends. Additional work has elucidated the benefit of assimilating ice thickness information for Arctic summer ice extent and ice-edge location predictions (e.g., Day et al., 2014a; Blockley and Peterson, 2018).

Boundary Forced Predictability and Projections of Sea Ice

On longer timescales, sea ice predictability arises from changes in climate drivers ("boundary forced predictability"). In the next decades, Arctic sea ice is projected to decline due to rising GHGs (e.g., Notz et al., 2020). However, internal variability remains an important source of uncertainty in the rate of future ice loss. Using numerous models, Bonan et al. (2021) found that internal variability accounts for 40%–60% of the summer ice loss uncertainty in the next decade, model structure uncertainty dominates in mid-century, and future emissions uncertainty dominates at the end of the twenty-first century. For winter sea ice, uncertainty associated with internal variability plays a role for longer lead times.

The continued influence of internal variability could mask the emergence of anthropogenically forced signals in the changing Arctic climate. A number of studies have used Earth system models to quantify when a forced signal emerges from the sizable internally generated Arctic climate variability. Even with this large noise, studies indicate that multiple aspects of forced Arctic change have emerged or will do so soon, including fall-winter surface warming (Hawkins and Sutton, 2012), an Arctic amplified signal of warming (e.g., England et al., 2021), and sea ice extent changes in both summer and winter (Landrum and Holland, 2020).

Internal variability also impacts the predictability of the timing of climate signals. For example, Jahn et al (2016) found an approximately 20-year range in the first occurrence of September ice-free Arctic conditions. An analysis of MMLE models confirms this important role of internal variability. In the ensemble mean, these models differ considerably in the timing of September ice-free conditions (Figure 3a), related in part to differences in their early twenty-first century state: the mean timing of ice-free conditions across the models is correlated to the annual cycle amplitude of 2000–2009 Arctic mean ice thickness at R = 0.95. Regardless of the mean timing of ice-free conditions, however, the uncertainty across all the models is sizable (Figure 3b).

SEA ICE MODEL ADVANCES SINCE CMIP6 AND IMPLICATIONS FOR IMPROVED PREDICTION

Many advances are underway to improve the simulation of sea ice within Earth system models. While this discussion focuses on sea ice model developments, their most significant climate impacts will be through their influence on feedbacks between the ice, atmosphere, and ocean. Better simulation of climate feedbacks will influence sea ice prediction. New ice model capabilities also allow for predictions of additional sea ice features (e.g., landfast ice) relevant to stakeholders. Although not a comprehensive list, here we describe some developments under consideration for the next class of coupled earth system models.

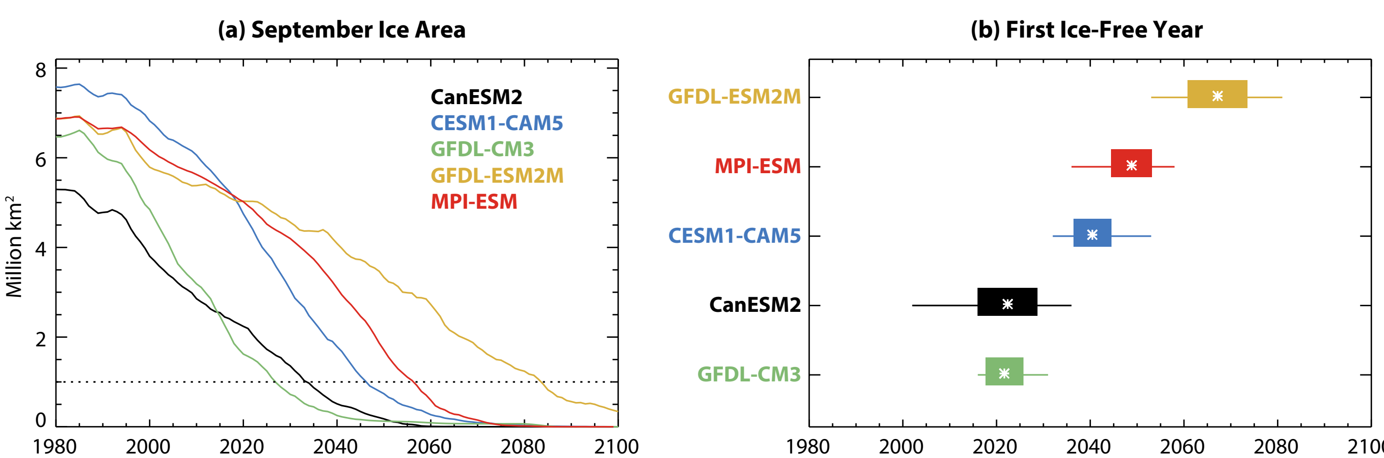

FIGURE 3. (a) Time series of ensemble-mean, Northern Hemisphere, September ice area from MMLE models. (b) Timing of first ice-free conditions, where the thin lines show the full ensemble range, the thick bars indicate the standard deviation, and the ensemble mean is indicated by white asterisks. CSIRO-Mk3-6-0 does not reach ice-free conditions by 2100. *Updated from Vavrus and Holland (2021)*

While plastic deformation produced by the (E)VP model approximates ice deformation (e.g., Mehlmann et al., 2021), recent improvements include Elastic Anisotropic Plastic (EAP) dynamics (Wilchinsky and Feltham, 2006; Tsamados et al., 2013), which accounts for subgrid regions of weakness in the ice cover that allow the ice to fracture in preferred directions. Brittle rheologies that incorporate damage are also being implemented in large-scale models.

Landfast ice—ice fastened to the coastline or seabed and lacking motion—is used by coastal communities for travel and hunting. As a solid barrier between the ocean and atmosphere, it limits direct fluxes of moisture and heat and can block a river's flow and cause flooding. A stress term added to the momentum equation better characterizes the interactions between grounded ridges and the seabed, improving the simulation of landfast ice in shallow water (Lemieux et al., 2016). To better simulate landfast ice in deeper water, the tensile strength of fixed, consolidated ice was also modified.

Areas covered by floes of different horizontal sizes have been represented using a floe size distribution analogous to the ice thickness distribution (Roach et al., 2018). Floe sizes change through five processes: new ice formation, welding of floes in freezing conditions, lateral growth, melt, and fracture of floes by surface waves. Fragmentation by waves makes ice more susceptible to summer melt and determines whether ice forms as pancakes or larger floes during freeze-up; this also influences ocean-atmosphere interactions. In the future, ice floe size characteristics will be used to influence waves in ocean models. Floe size can also influence drag by wind and currents on the ice surface. Most climate models use constant drag coefficients, but new developments allow the drag coefficients to depend on the ridges and keels of deformed ice and on ice edges (Tsamados et al., 2014).

New developments in modeling also focus on biogeochemistry and ecosystem dynamics (e.g., Duarte et al., 2017; N. Jeffrey et al., 2020) by tightly coupling ice physics and the chemistry and biology within the brine network. When ice forms, the crystalline structure extrudes brine, some of which is captured in pockets within the ice. These brine pockets expand and contract with changing temperature, becoming conduits for meltwater and nutrient-laden seawater. Organisms such as algae that live within the brine network, seed oceanic algal blooms in winter and early spring, thus serving as a fundamental source for primary production in polar waters. Incorporation of sea ice biogeochemistry into Earth system models will enable better prediction of marine ecosystems. It will also influence coupled feedbacks as ice algal production affects the flux of dimethyl sulfide (DMS), which is important in forming cloud condensation nuclei.

While sea ice predictions hinge crucially on interactions with the atmosphere and ocean, some developments target internal sea ice model representations for improved short-term or fine spatial scale predictions. These new approaches have the potential to revolutionize the representation of sea ice in climate simulations. For instance, the neXtSIM model (Rampal et al., 2016) uses a Lagrangian advection scheme in which the mesh moves with the ice, employing a brittle rheology to simulate properties of ice drift and deformation. New efforts to capture both Lagrangian and anisotropic sea ice behavior include discrete element modeling (Herman, 2016) in which aggregates of ice floes form the numerical elements.

Such advances will enable more realistic interactions with the atmosphere and ocean models and provide the capability to simulate more complex sea ice features. This will ultimately allow for enhanced prediction of stakeholder-relevant aspects of the changing Arctic. Note however that predictions of sea ice are also strongly influenced by the simulated atmosphere and ocean, and so improvements in ice model processes alone are not a panacea. Thus, developments are also needed within atmospheric and oceanic models to better simulate winds, radiation fields, and ocean heat transport, among other properties.

CONCLUSIONS

Here we have provided a high-level review of sea ice models used for climate simulations and recent advances made with these models to understand seasonal to multi-decadal sea ice predictability. This has been enhanced with new analysis from the MMLE (Deser et al., 2020), which indicates that while many findings are robust across models, there remain model structural uncertainty that affects the magnitude of predictive signals and attribution of the factors responsible for historical ice loss. Comparison across models of simulated sea ice predictability/variability mechanisms and their similarity to observations is needed to further elucidate factors of ice predictability and change.

Because sea ice plays a critical role in the climate system through its influence on the surface heat budget and the hydrological cycle, models need to adequately represent processes that affect these climate interactions. The sea ice components used in current Earth system models have advanced considerably in the last decade, allowing for more realistic treatment of ice dynamics, thermodynamics, and spatial heterogeneity and thus improving the simulation of climate feedbacks. New advances are continuing to improve the realism of sea ice and its interactions with the atmosphere and ocean. For example, models that simulate a floe size distribution allow for wave-ice coupling, and the incorporation of sea ice biogeochemistry enables new feedbacks for the marine ecosystem and polar cloud properties. While these elements have not yet been included in CMIP studies, they provide new avenues for research and Earth system prediction.

These advances will build on a body of research that uses Earth system models to query the predictability of Arctic sea ice. This work has shown that sea ice area is predictable on seasonal timescales and has highlighted predictability mechanisms, thus informing ice forecasting systems for more skillful predictions. Recent research has also elucidated the critical role of internal variability in the climate system and the influence this internal variability has on multi-decadal ice trends. Evidence suggests that internal variability has reinforced anthropogenically driven summer ice loss in the Arctic by as much as 50%, with atmospheric circulation variability playing a key role. While internal variability is a sizable source of uncertainty in longer timescale predictions, anthropogenically driven changes in the Arctic are also large, and many anthropogenic Arctic climate changes have already emerged from the internal climate noise.

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Observing Arctic Sea Ice

By Melinda A. Webster, Ignatius Rigor, and Nicholas C. Wright

ABSTRACT. Our understanding of Arctic sea ice and its wide-ranging influence is deeply rooted in observation. Advancing technologies have profoundly improved our ability to observe Arctic sea ice, document its processes and properties, and describe atmosphere-ice-ocean interactions with unprecedented detail. Yet, our progress toward better understanding the Arctic sea ice system is mired by the stark disparities between observations that tend to be siloed by method, scientific discipline, and application. This article presents a review and philosophical design for observing sea ice and accelerating our understanding of the Arctic sea ice system. We give a brief history of Arctic sea ice observations and showcase the 2018 melt season within the context of five observational themes: spatial heterogeneity, temporal variability, cross-disciplinary science, scalability, and retrieval uncertainty. We synthesize buoy data, optical imagery, satellite retrievals, and airborne measurements to demonstrate how disparate data sets can be woven together to transcend issues of observational scale. The results show that there are limitations to interpreting any single data set alone. However, many of these limitations can be surmounted by combining observations that cross spatial and temporal scales. We conclude the article with pathways toward enhanced coordination across observational platforms in order to: (1) optimize the scientific, operational, and community return on observational investments, and (2) facilitate a richer understanding of Arctic sea ice and its role in the climate system.

A BRIEF HISTORY

Over the centuries, sea ice observations have come in many forms, designed for different needs and covering different scales. The earliest observations began thousands of years ago to meet the needs of Arctic Indigenous peoples. By using sea ice as a platform for subsistence hunting, traveling over ice for long distances, and sharing experiences from one generation to the next, their knowledge of ice behavior, stability, and characteristics was formed. A rich and immeasurable understanding of sea ice continues to grow to this day, as sea ice is still a cultural livelihood for Arctic Indigenous communities (Krupnik et al., 2010; Huntington et al., 2017).

During the age of exploration, mariners navigated through the outer reaches of the Arctic ice pack, drafting its periphery onto coarse maps of lands and seas. The rise of routine, quantitative sea ice observations came with the explosion of whaling operations and expeditions. Iterative maps, reworked time and time again, began to formulate a clearer picture of the marginal ice zone and the seasonality of Arctic sea ice. The observational record expanded immensely during this time, so much so that these early observations of sea ice coverage were combined with modern-day satellite data to extend the record back to 1750 (Divine and Dick, 2006) and 1850 (Walsh et al., 2016). In recent decades, paleoclimate proxies from marine sediments, land ice cores, and coastal records have been used to reconstruct the sea ice record back even further to thousands of years (Polyak et al., 2010; Abram et al., 2013), revealing new insight on the natural variability of Arctic sea ice.

From the late nineteenth century and through the twentieth century, the Fram Expedition (1893–1896), drifting ice stations, autonomous drifting buoys, airborne campaigns, and submarine surveys bolstered the foundation of sea ice observations. A multinational, coordinated endeavor called the International Polar Year (IPY) began in 1882 with the aim of collecting geophysical observations of the polar regions year-round (Barr and Lüdecke, 2010). IPY was the driving force for many of these field activities. Collectively, they produced the first quantitative records of sea ice circulation (Thorndike and Colony, 1982) and sea ice properties (Nansen, 1902), including ridge size and distribution (Romanov, 1995), melt ponds (Nazintsev, 1964), ice draft (Gossett, 1996), and snow depth and density (Warren et al., 1999). Carefully pieced together, these data sets provided the first pan-Arctic, multidecadal, year-round time series; some have since served as baselines from which long-term changes in Arctic sea ice properties have been measured (e.g., Webster et al., 2014; Kwok, 2018).

In the mid-twentieth century, the age of remote sensing profoundly advanced our observational capabilities. Polar-orbiting satellites collect near-continuous data over vast spatial scales, readily filling in gaps in the pan-Arctic picture. These satellites also relay observations from buoys on drifting sea ice in real time. In the late 1970s, passive microwave remote sensing initiated the longest, most consistent observational record of sea ice on the pan-Arctic scale. This iconic record spans more than 43 years, monitoring sea ice day and night, in cloudy and clear skies, and has proven instrumental in unveiling the acute sensitivity of Arctic sea ice to global warming (Fox-Kemper et al., 2021). The passive microwave record continues to serve as a valuable metric against which to test the ability of climate models to accurately simulate the Earth system (Notz and SIMIP Community, 2020).

In recent decades, technology has honed our remote-sensing capabilities. Airborne campaigns have become testbeds of lidar altimetry (Ketchum, 1971), synthetic aperture radar (Holmes et al., 1984), and electromagnetic soundings (Kovacs et al., 1987). Sea ice properties previously unresolvable from air and space now include ridges (Fredensborg Hansen et al., 2021), melt ponds (Wright and Polashenski, 2018; Farrell et al., 2020), freeboard and thickness (Ricker et al., 2017; Kwok et al., 2019), sea ice age (Tschudi et al., 2020), snow depth (Rostosky et al., 2018; Kwok et al., 2020), and leads (Reiser et al., 2020). Conjointly,

PREVIOUS PAGE. Scientists collecting in situ observations of sea ice, ice and ocean algae, and upper ocean properties on NASA's Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE) expedition in July 2011. *Photo credit: Melinda Webster* the temporal resolution of satellite data is ever refining, enabling the collection of process-oriented information such as divergence, convergence, shear, and vorticity of the ice pack along with melt pond evolution and more. Radio triangulation was used early on to locate drifting buoys to within ~25 km. With the advent of satellites, Doppler positioning of buoys increased location accuracy to ~300 m, then ~2–3 m with the Global Positioning System, and centimeter-scale with the newer geodetic-quality global navigation satellite system (GNSS) buoys. The Iridium constellation of satellites now allows continuous temporal coverage by drifting buoys.

This brings us to today, a time of plentiful Arctic sea ice observations. In the sections that follow, we demonstrate current observational capabilities across local, synoptic, and pan-Arctic scales using a wide range of in situ and remote-sensing tools. We showcase sea ice conditions in 2018, with an emphasis on the Beaufort and Chukchi Seas, where significant summertime ice loss has occurred in recent decades (Frey et al., 2015). We present complementary data sets collected from field and airborne campaigns, buoy deployments, and Lagrangian tracking by satellites. The results reveal that, through coordinated efforts across communities, a richer understanding of Arctic sea ice system behavior is readily within reach.

THE ISSUE OF SCALE

Our capability to observe Arctic sea ice is better than ever before, but many knowledge gaps in the Arctic sea ice system remain—and filling in these gaps is a balancing act. There are pressing needs to observe Arctic sea ice across a multitude of spatial and temporal scales, from improving the development of retrieval algorithms and data assimilation in weather and sea ice forecasts to monitoring climate-scale changes. Fundamental to all measurements are their observational scales, the times and spaces at which the measurements can be made (Blöschl and Sivapalan, 1995). The observational scale can be a point measurement, such as a snow depth value obtained with a ruler, or a multi-kilometer footprint of a satellite sensor, as with passive microwave retrievals of sea ice concentration. Although the boundaries between scales are becoming increasingly blurred (Figure 1), the scales at which observations are made often differ from the scales at which processes occur (Blöschl and Sivapalan, 1995). For satellite retrievals, the spatial resolution of gridded products differs from that of a satellite's footprint. Furthermore, what is measured within a satellite footprint may not statistically represent the average of the variable being derived. Collectively, these issues pose considerable challenges in the appropriate interpretation of in situ and remotely sensed observations.

As a case example, consider the relationship between snow depth and sea ice thickness in the Arctic in mid-spring. On point measurement scales (<0.5 m footprint), snow depth and the thickness of smooth sea ice beneath it are often negatively correlated, with locally thin sea ice having locally thick snow, and vice-versa. This inverse relationship arises due to snow's high insulating capacity, which inhibits heat flux and sea ice growth (Sturm et al., 2002) and the greater susceptibility of wind-blown snow to be deposited in surface depressions, such as on top of refrozen melt ponds (see Figure 11d in Perovich et al., 2003).

In contrast, airborne retrievals of snow depth and sea ice thickness (Kurtz et al., 2015) show the opposite result. The airborne retrievals, as 40 m averages, yield a *positive* correlation between snow depth and sea ice thickness, meaning that on thicker ice, there is deeper snow, and vice versa. Although the two sets of observations seemingly contradict one another, both are correct for the spatial scales over which they are measured. Their differences underscore the importance of using the process scale to guide the interpretation of different observational scales (Blöschl and Sivapalan, 1995). Point measurements are effective in capturing local interactions and isolating mechanisms, making them central to gaining a deep understanding of physical processes and improving their representation in models; however, their broad-scale application across regions is limited.

Larger-scale measurements, such as airborne and satellite retrievals, are an integration of numerous processes, with large-scale processes having a stronger influence than small-scale processes.

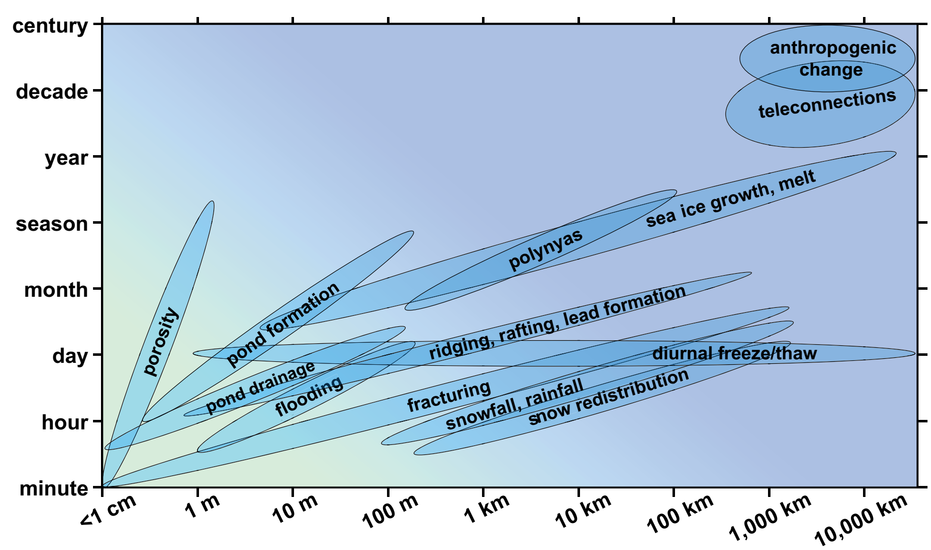

FIGURE 1. Examples of sea ice processes that occur over multiple spatial and temporal scales. The scales at which measurements are made often do not match the scales at which phenomena occur. The green background shading indicates scales over which in situ measurements are made, while the purple shading represents scales at which remote sensing retrievals are possible. *Adapted from Blöschl and Sivapalan (1995) for the Arctic sea ice environment*

This can be readily seen in the pan-Arctic distribution of snow on Arctic sea ice (Webster et al., 2018). The deepest snow is found in regions with higher snowfall rates, older sea ice, and rougher sea ice. Unlike point measurements, larger-scale observations are better suited for monitoring pan-Arctic distributions and assessing the ability of Earth system models to simulate the cumulative effect of different processes on variables.

A SAMPLE IN TIME

Temporal sampling of Arctic sea ice has greatly improved over the decades. Historically, most in situ measurements were made during spring-summer when the polar day permitted airborne surveys and landings on sea ice, and the summer retreat of ice allowed the passage of ships. From these early observations, weather patterns were quantified and related to patterns in sea ice drift around the Beaufort Gyre and along the Transpolar Drift Stream (Figure 2a). The discovery of the persistent Beaufort High in sea level pressure resulted from these observations.

Deployment of autonomous buoys (Polashenski et al., 2011; Lei et al., 2016; Wang et al., 2016; Perovich et al., 2021) and moored observatories (Spreen et al., 2020) enabled year-round observations of surface air pressure and temperature, upper ocean temperature and salinity, and other geophysical parameters. The temporal resolution of buoy observations was previously limited to the frequency of satellites passing overhead, resulting in sub-daily sampling on a timescale of synoptic atmospheric and oceanic processes. Now, with continuous coverage of the North Pole by Iridium, observations are considerably more frequent and can reveal short-lived processes. For example, hourly observations can capture the fracturing, ridging, and rafting of sea ice (Figures 2 and 3d), as well as the inertial oscillations in sea ice motion (Figure 2b). Processes that quickly thicken the ice relative to slow thermodynamic growth can readily be monitored by analyzing the areal geometric changes between buoy arrays over nested spatial scales (e.g., the Distributed Network in Nicolaus et al., 2022). Such high-frequency observations provide new opportunities for studying atmosphere-ice-ocean interactions: the impact of tides on sea ice surface roughness, the role of tides and wind-driven circulation in the evolution and distribution of sea ice thickness, and the influence of net divergence or convergence on geographic differences in summer melt processes, to name a few.

The amount of data transmitted by buoys has also increased dramatically, from a few bytes to hundreds of bytes. In the near future, the Iridium Certus system will enable the transmission of thousands of bytes. Together with higher data transmission, current electronics and batteries permit the collection of hourly observations. Further advances in low-power electronics and significant improvements in the power density of batteries have spurred initiatives within the World Meteorological Organization and Intergovernmental Oceanographic Commission to deploy buoys that transmit observations every 10 minutes.

SPATIAL HETEROGENEITY

The heterogeneity of Arctic sea ice is at its most vibrant display during the melt season. From May to September, the vast

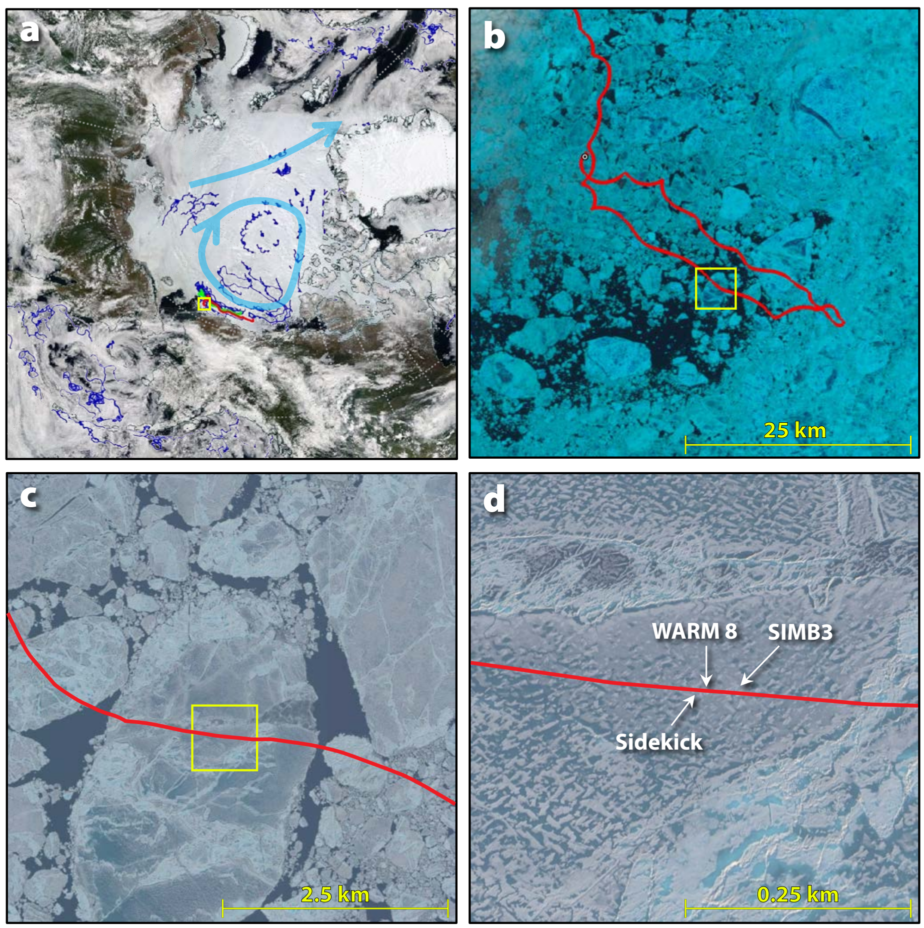

FIGURE 2. Maps of buoy drifts overlaid on satellite images of increasing resolution for June 2018. The yellow boxes indicate the areas zoomed-in from one figure panel to the next. (a) Blue dots show buoy positions for April 1–June 30, and the green and red lines show the drifts of buoy Clusters 1 and 2 during the same period, overlaid on a 1 km resolution MODIS true-color scene from June 22. The thick, light blue lines and arrows are schematics depicting the circulation of the Beaufort Gyre and the Transpolar Drift Stream. (b) The Cluster 2 drift overlaid on a 10 m resolution Sentinel-2 scene from June 24. (c) The Cluster 2 drift overlaid onto a ~0.4 m resolution WorldView-3 scene from June 28. (d) A WorldView-3 scene from June 28, where, upon closer inspection, individual buoys can be identified. *©2018 DigitalGlobe NextView License*

expanse of the snow-covered ice pack transforms into a mosaic of floes composed of bare and ponded sea ice. Melt ponds decrease the surface albedo and increase the amount of absorbed and transmitted sunlight (Perovich et al., 2002a). Features of the sea ice cover, like melt ponds, are highly variable in their spatial distribution, and they often change with time-varying processes. The scales over which these features change dictate the type of sensors that can be used to detect them and the frequency at which they can be sampled. For example, fully resolving individual melt ponds requires observing sea ice at the meter scale or finer. To capture pond drainage events, daily temporal resolution is needed at a minimum.

To explore spatial heterogeneity in sea ice observations, consider the evolution of melt ponds at the locations of two drifting buoy clusters in summer 2018 (Figures 2 and 3). Clusters 1 and 2 were tracked with high-resolution optical satellite (WorldView) imagery as they drifted across the Beaufort and Chukchi Seas. The images were analyzed using the open source sea ice processing algorithm (Wright and Polashenski, 2018) to detect the areal fraction of each image that falls into one of four surface categories: (1) snow and bare sea ice, (2) gray (thin or slushy) ice, (3) melt ponds or submerged ice, and (4) ocean.

Figure 3d shows a bird's-eye view of the surface conditions. These subsets reveal how truly heterogeneous the Arctic sea ice cover can be on meter-to-kilometer scales. The smooth sea ice on the lower portion is representative of undeformed first-year sea ice, while the rougher, more variable surface in the upper portion is characteristic of multiyear sea ice. Both ice types coexist on the same floe, but the progression of melt ponding differs between the two. This arises from dissimilar surface roughness and ice permeability, which affects the areal coverage and persistence of melt ponds. Yet, even across floes of smooth first-year sea ice, there can be contrasting discrepancies in melt pond coverage, with widespread ponding on one floe and complete absence of ponds on another.

The different timing and distribution of melt ponds lead to locally variable rates of melt. If melt ponds form early in one location, that surface will undergo greater melt earlier in the season than unponded ice due to positive albedo feedback. If an area has larger melt ponds, its melt rate will be higher than that in areas with smaller melt ponds. At Cluster 1 (Figure 3d), melt pond formation began earlier on the multiyear ice portion. Despite this earlier formation, the melt ponding on the smooth, first-year ice was more extensive by late June in 2018, and the first-year ice soon deteriorated into a skeletal-like structure, full of holes where ponds once were. Shortly thereafter, the first-year portion of the floe broke up, notably weeks earlier than the multiyear portion. When considering sea ice mass balance, whether the timing of formation or areal coverage of melt ponds is more important remains an open question, but this may be better understood with future coordinated tracking of drifting buoys by satellites.

Beyond the kilometer scale is the mesoscale (~10 km–1,000 km), a scale at which local heterogeneity starts to diminish and geographic differences and predominant sea ice conditions become increasingly important. Continuing with our melt pond example, we turn to the drifting buoy clusters to examine the scaling behavior of spatial heterogeneity. The two clusters remained ~150 km apart (Figure 2) as they drifted with the winds and ocean currents in May-August in 2018, and hence, they were subjected

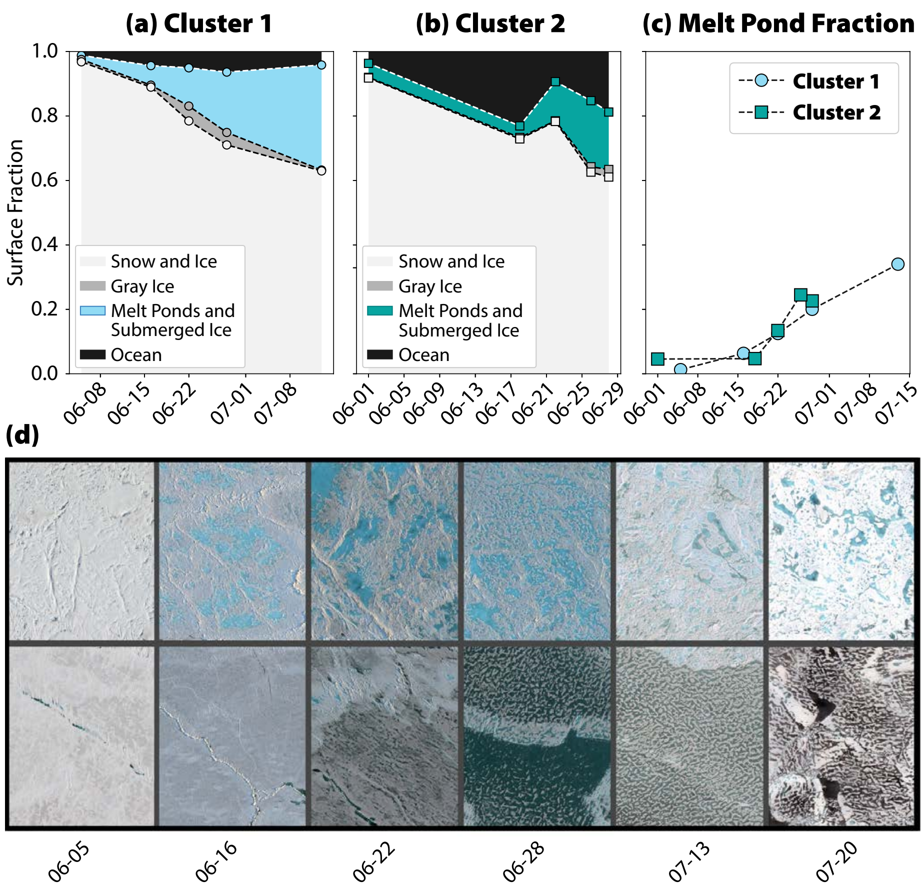

FIGURE 3. The evolution of the total areal surface fraction for (a) Cluster 1 and (b) Cluster 2. (c) The melt pond fraction, given as the ponded ice fraction. (d) A subset of pond evolution from WorldView images of Cluster 1. Panels in (d) show pond formation on multiyear (top row) and first-year (bottom row) ice. Each panel is 400 m x 400 m. Dates are presented as "month-day." *©2018 DigitalGlobe NextView License*

to similar synoptic conditions: similar snowfall, rainfall, temperatures, and radiative forcing. Accordingly, the average snow depths in their broader areas were alike, 0.19 m vs 0.18 m for Clusters 1 and 2, respectively. Even so, the physical state of the sea ice differed between the two clusters. In mid-April 2018, NASA's Operation IceBridge airborne mission flew over both sites, measuring considerably thicker ice at Cluster 1 (2.2 ± 1.7 m), while Cluster 2 had relatively thinner sea ice (1.4 ± 1.1 m). Cluster 1's location was also slightly northward and farther from the ice edge, which, together with having thicker ice, may have contributed to its longer survival during the melt season.

While there are some differences in the evolution of surface conditions between the two clusters at the 15 km × 15 km scale—notably that there was more open water and thinner, smoother sea ice at Cluster 2—the overall evolution of melt ponds was not significantly different between the two. These results, consistent with previous findings, reveal an important relationship between sea ice surface heterogeneity and scale: the coverage of melt ponds is highly variable across small spatial scales (tens of meters), but becomes increasingly consistent across larger scales (tens of kilometers) (Perovich et al., 2002b; Wright and Polashenski, 2018; and others). This phenomenon is known as the "aggregate scale," or the scale at which the observed property is statistically representative of the larger region, and has been found to be tens of kilometers during the melt season (Perovich et al., 2002b). In essence, the local scale heterogeneity (Figure 3d; ~400 m × 400 m) collectively combines into a single aggregate scale (~15 km × 15 km) whose result reveals itself in the time series of the ponded ice fraction (Figure 3c).

SYNTHESIZING DISPARATE OBSERVATIONS

Drifting buoys, moorings, and field campaigns typically have higher frequency sampling than air- and spaceborne missions, and the lower sampling frequency of satellite products limits their ability to detect short-lived events. In Figure 4, we combine disparate pieces of information to highlight the value of high frequency sampling and the advantages of co-deploying complementary instruments, a common practice of collaborators in the International Arctic Buoy Programme

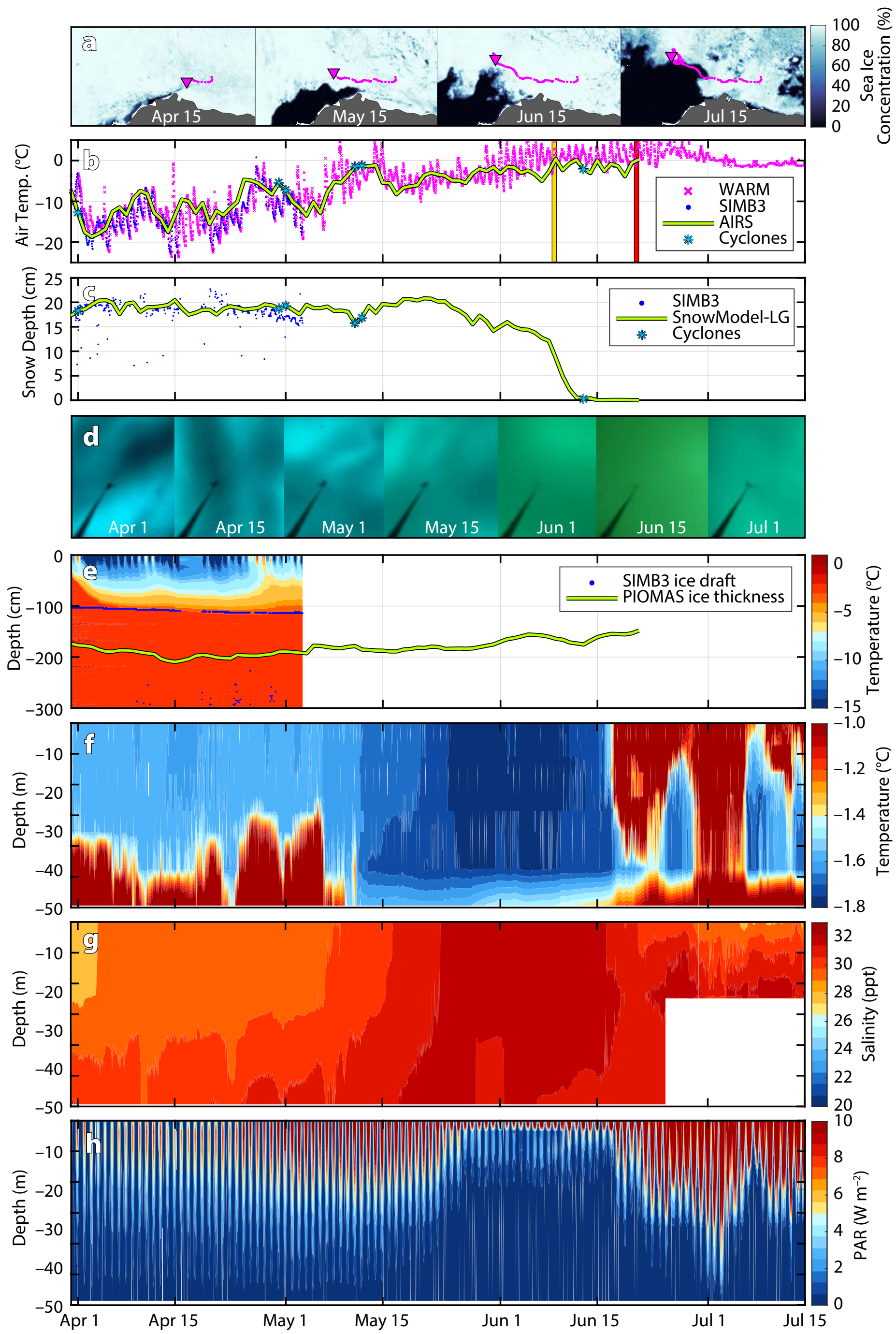

FIGURE 4. A compilation of satellite, model, and buoy data from Cluster 2 during 2018. (a) ARTIST Sea Ice (ASI) concentrations. (b) Air temperatures from the seasonal ice mass balance (SIMB), WArming and iRradiance Measurements (WARM) buoy, and derived by satellite (Atmospheric Infrared Sounder). Storm events are marked by cyan asterisks and satellite-derived dates of early onset (yellow) and continuous (red) melt by vertical bars. (c) Snow depth from the SIMB and Lagrangian snow-evolution model (SnowModel-LG). (d) Under-ice photos from the WARM buoy. (e) In-ice and ocean temperatures with ice drafts from the SIMB and simulated sea ice thickness from Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS). (f) Ocean temperature from the WARM buoy. (g) Ocean salinity from the WARM buoy. (h) Photosynthetically active radiation (PAR) from the WARM buoy.

(IABP; https://iabp.apl.uw.edu/). The data in **Figure 4** come from several sources, including compiled data sets found in the Lagrangian ice parcel database (Horvath et al., 2021) and in ice mass balance (IMB; Perovich et al., 2021) and WArming and iRradiance Measurements (WARM; Hill et al., 2018) buoy data.

In **Figure 4b**, consider the effects of temporal resolution on observed temperature. The buoy data exhibit a distinct diurnal cycling of temperatures, while the satellite-derived temperatures show a more slowly varying behavior and no diurnal cycling whatsoever. Different temporal sampling and different measurement techniques can produce substantially different results for the same phenomenon. The date of melt onset is an especially insightful example of the large differences that can arise between in situ and satellite-derived measurements (**Figure 4b**). In mid-May, in situ temperatures exceeded 0°C and surface melt was observed. Meanwhile, the satellite retrievals show a melt onset date three weeks later (**Figure 3d**). Deriving air temperature by satellite requires several assumptions, including those about emissivity, a property that is strongly influenced by the surface state and atmospheric water content (Ulaby et al., 1981; Jackson et al., 2006). Thus, discrepancies between in situ and satellite data sets can arise if assumptions in satellite retrievals do not truly reflect the ever-changing surface and atmospheric conditions. A three- to four-week discrepancy in the timing of melt onset changes the interpretation of cause and effect when it comes to interactions among the atmosphere, sea ice, and ocean, especially regarding primary productivity and melt processes.

And timing is everything for sea ice algae. Ice algae are a fundamental component of the Arctic marine food web (Kohlbach et al., 2016; Wiedmann et al., 2020) and are highly sensitive to the thickness of snow and sea ice due to their adaptation to low irradiance levels (Leu et al., 2015). At Cluster 2, the timing and duration of snow melt (**Figure 4c**) coincided with a notable ice algal bloom (Victoria Hill, Old Dominion University, *pers. comm.*, 2021), resulting in less photosynthetically active radiation (PAR) in the upper ocean (**Figure 4h**). As melt pond formation progressed (**Figure 3**), irradiance levels returned to near-normal levels. The ice algae bloom gradually diminished (**Figure 4d**), but it had left its mark: the long duration of low ocean PAR levels substantially disrupted phytoplankton productivity in the upper water column for the season (Victoria Hill, Old Dominion University, *pers. comm.*, 2021).

Auxiliary information, such as ocean temperature and salinity (**Figure 4f,g**), provides added insight on potential nutrient loading and also on environmental conditions leading to abrupt sea ice changes. This case study illustrates how coordinated deployments enable single discipline and cross-discipline analyses, which can greatly aid system science investigations.

SCALABILITY AND ITS IMPACTS

One of the most powerful traits of Arctic sea ice is its high albedo, which results in reflection of ~40%–80% of solar radiation back into space, compared to only ~7% reflected by the open ocean (Perovich et al., 2011). Here, we estimate solar heat input into the ice-free and ice-covered Arctic Ocean to examine how small-scale heterogeneity manifests across spatial scales (**Figure 5**). We estimate solar heat input using a daily mean downwelling solar flux from ERA5 reanalysis (Hersbach et al., 2018), prescribed surface albedo as in Perovich et al. (2011), stages of melt and freeze onset dates derived from satellite data (Markus et al., 2009), and sea ice concentrations also derived from satellite data. This exercise was performed using three sea ice concentration retrievals, each covering a different spatial scale: WorldView (WV) ~15 km scene with ~0.4 m resolution (**Figure 3**), ARTIST Sea Ice (ASI) 6.25 km grid (Spreen et al., 2008), and Climate Data Record (CDR) 25 km grid (Meier et al., 2021).

First, consider the cumulative heat input on the smallest scale (6.25 km to 25 km) at the buoy clusters, where coincident pixels from the three sea ice concentration retrievals were evaluated (**Figure 5**, right: black, orange, and cyan lines). The estimates from the buoy clusters use the same solar flux and the same prescribed albedo for sea ice and open water; the differences arise solely from the sea ice concentrations, which are within ~1%–2% of one another throughout the year except for July, when ASI and CDR show 25% less sea ice coverage than the WV retrieval. The 25% difference in July sea ice coverage results in ~70–90 MJ m^{-2} more heat going into the sea ice and open ocean. This is equivalent to ~0.2–0.3 m of additional sea ice melt in a region that had, on average, 1.7 m thick ice prior to melt onset.

There are several possibilities for the discrepancies in the solar heat input estimates. For one, the passive microwave retrievals (ASI, CDR) may erroneously detect melt ponds as open water. In the range of microwave electromagnetic radiation, melt ponds are sufficiently deep to mask the emissivity of the underlying sea ice and produce an emissivity similar to that of open ocean (Ulaby et al., 1981). Thus, the passive microwave retrievals may underestimate sea ice concentrations and overestimate solar absorption when melt ponds are present. Previous work (Rösel et al., 2012) suggests a low bias in passive microwave sea ice concentrations by as much as ~40% due to melt ponds. Approaches blending higher-resolution optical imagery with passive microwave may be a fruitful way forward in improving sea ice retrievals during the melt season, as the use of optical imagery alone is limited by clouds in summer.

Discrepancies in the estimated solar heat input could also stem from a sampling issue. Here, we examined grid cells of the satellite products at each buoy cluster, with the centers askew from one another. Moreover, the clusters are located in a markedly dynamic environment; the marginal ice zone is susceptible to large changes in ice coverage over relatively short periods, which can result in retrieval differences if satellites collect data at different times. To explore the differences in spatial resolution, we performed the same exercise using the ASI and CDR products on regional and pan-Arctic scales. The higher resolution product (ASI) yields more solar heat input (30 MJ m^{-2}) for both the Beaufort and Chukchi Sea regions and Arctic-wide. This equates to ~0.1 m of additional sea ice melt, which is distributed fairly uniformly across the Arctic, across ice concentrations, and between multiyear and first-year ice regions.

While there are significant differences between passive microwave products and their input data (Ivanova et al., 2015; Meier and Stewart, 2019), the differences in the solar heat input estimates shown here are still noteworthy. Collectively, they point to the need to continually revisit and refine remotely sensed sea ice observations as technology advances and our ability to resolve surface processes improves. Much like our understanding of the Arctic sea ice system, the techniques used to document sea ice conditions are ever-evolving, and there is added value in modernizing past observations to retain and reestablish a baseline from which long-term changes can be measured.

AUSPICIOUS DIRECTIONS

Arctic sea ice loss is expected to continue over the next decades, with most model projections showing the first ice-free (extent under 1 million square kilometers) Arctic summer to occur by 2050 (Notz and SIMIP Community, 2020). As sea ice loss continues and technologies advance, autonomous systems and remote sensing will play increasingly larger roles in sea ice observations. As shown in the drifting cluster examples, harmonization between different observational scales and techniques augments the science that can be achieved with observational investments. Instrument arrays with complementary sensors are of particular interest since they enable cross-disciplinary science. They can capture the concomitant changes in atmospheric, sea ice, biological, and oceanic conditions, allowing for better understanding of processes on local scales. Coordinated airborne measurements and Lagrangian tracking of drifting arrays by satellite are at the forefront of sea ice observations. These types of observations provide the context necessary for relating local-scale heterogeneity and temporal variability to aggregate-scale properties and evolution. In particular, such fine-scale observations enable the scalability of in situ measurements for relating to coarse-resolution satellite products and model output.

Although future field operations may encounter greater risks with a thinner, less stable Arctic sea ice cover, in situ observation will be equally, if not more, valuable. As noted in Gerland et al. (2019), there are only a few clusters of ice and ocean buoys across Arctic sea ice at any given time, and there are recurring gaps in the observing network during winter when buoys drift into the Transpolar Drift Stream and away from the Eurasian coast. These gaps increase the uncertainties in our analyses of weather, sea ice, and climate change (Inoue et al., 2009; Inoue, 2021), and more efforts are needed to reseed the Arctic Observing Network during winter. Similarly, routine observations of sea ice conditions from ships initiated by the "Ice Watch" Arctic Shipborne Sea Ice Standardization Tool (ASSIST) Data Network (https://icewatch.met.no/)

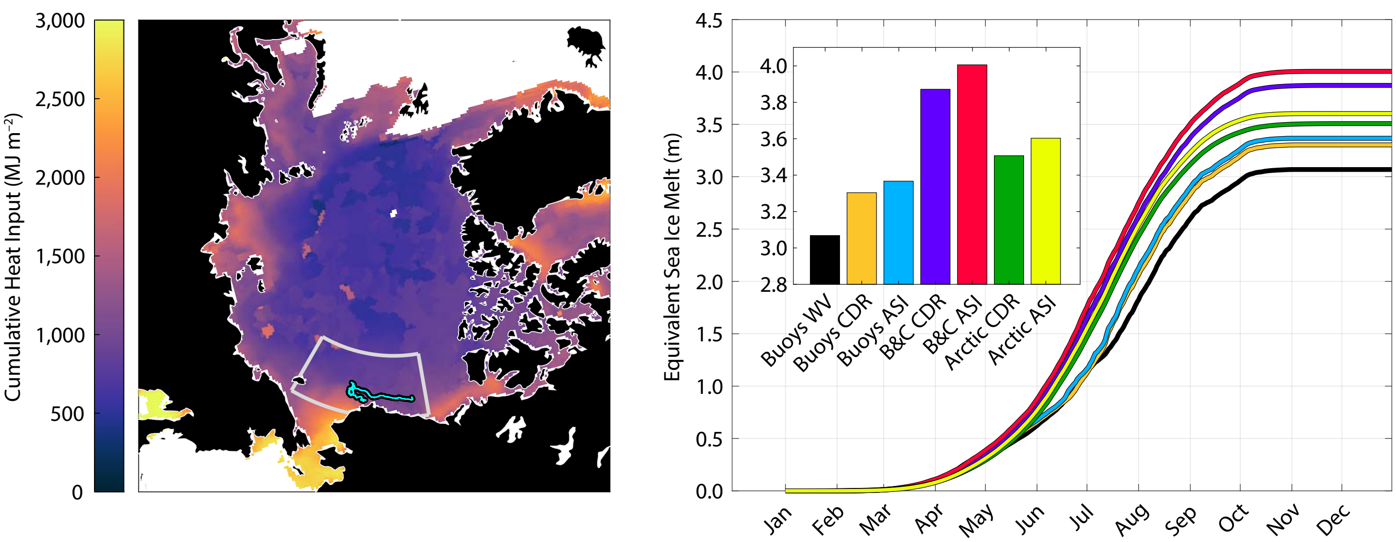

FIGURE 5. (left) Total annual solar heat input into the ice and ocean in 2018 from Climate Data Record (CDR) sea ice concentrations. Tracks of the drifting buoy clusters are drawn in cyan, and the region of the Beaufort and Chukchi Seas is outlined by the light gray box. (right) Equivalent amounts of sea ice melt based on the mean value of total annual solar heat input, an ice density of 900 kg m^3, latent heat of fusion of 0.335 MJ km^{-1}, and different sea ice concentration retrievals. Going from small to large scales, the estimates are derived from the buoy clusters (Buoys WV; Buoys CDR; Buoys ASI), the Beaufort and Chukchi Sea region (B&C CDR; B&C ASI), and the Arctic, averaged over 67°N–90°N (Arctic CDR; Arctic ASI). The inlaid bar chart displays the equivalent amounts of ice melt (meters) at the end of 2018. In reality, a small amount of heat would be lost through turbulent fluxes and other processes, and less ice melt would occur. B&C = Beaufort and Chukchi Sea region. ASI = ARTIST Sea Ice. CDR = Climate Data Record. WV = WorldView.

would benefit from the increasing number of ships operating in the Arctic.

New remote-sensing technologies, such as dual-sensor altimetry, will also require considerable ground validation programs to account for the anticipated environmental changes to come. The shift to seasonal, more saline sea ice, more frequent freeze-thaw cycling, and more frequent rainfall (Fox-Kemper et al., 2021) will lead to a more complex vertical substrate of snow and sea ice, posing greater challenges for remote-sensing retrievals in the future. To sufficiently quantify uncertainties and biases for scientific reliability, ground-truthing observations should optimally cover a wide range of snow and sea ice conditions. Ideally, such ground-truthing activities can be done in coordination with other observational efforts, such as drifting array deployments and planned field programs, including ecosystem studies, to foster collaboration and inclusivity across the broader community.

Lastly, models can optimize observations by helping guide observational priorities. Sensitivity experiments and observational assessments are effective in pinpointing sources of deficiencies in models, such as specific processes and physics. Targeting observations for such processes can help advance incomplete representations of heterogeneity, variability, and atmosphere-ice-ocean-ecosystem interactions in models. Model inter-comparisons can elucidate regions and seasons where intra-model spread is large, and subsequently direct where and when observing systems are best placed. By bridging observational and modeling efforts, we can elevate the scientific, operational, and community return on investments, and better anticipate the cascading effects of the changing Arctic sea ice system.

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SIDEBAR > The ICESat-2 Mission and Polar Sea Ice

By Ron Kwok

The altimetry from NASA's ICESat-2 orbiting observatory addresses science requirements that pertain to the monitoring of changes in sea ice, ice sheets, ocean circulation, and vegetation biomass (Markus et al., 2017). Retrievals from the ICESat-2 (IS-2) mission add to the valuable multidecadal record of elevation changes from previous and forthcoming altimetry missions for understanding geophysical processes and for climate monitoring, forecasts, and projections. Launched in September 2018, the second-generation spaceborne lidar onboard the Advanced Topographic Laser Altimeter System (ATLAS) employs a unique photon-counting approach for profiling the surface. ATLAS utilizes a low pulse-energy laser (at 532 nm) in a six-beam configuration that allows cross-track profiling and improved spatial resolution. On the surface, three beam-pairs (with intrapair spacings of 90 m) trace ground tracks separated by about 3.3 km. Each pair consists of a strong and a weak beam, and the pulse energies of the strong beams are about four times those of the weak. For range determination, photon detectors allow centimeter-level roundtrip timing of transmitted photons and individual scattered photons from the surface. At orbital velocities and a pulse repetition rate of 10 kHz, laser footprints of ~11 m (in diameter) are separated by ~0.7 m. This can be contrasted with the 167 m spacing between nonoverlapping ICESat (operated between 2003 and 2009) lidar footprints ~50–70 m in diameter.

For the ice-covered oceans, ATLAS is tasked with providing the height of sea ice and local sea surfaces for calculation of freeboard—the vertical height of the floating ice above the local sea level. For freeboard determination, high-resolution ATLAS samples (of tens of meters with vertical precision better than a few centimeters) are key to obtaining local sea level in open leads as the heights of samples in narrow openings could easily be contaminated by adjacent ice surfaces with higher surface reflectance. Assuming isostatic equilibrium of the floating ice, the retrieved total freeboard (snow plus ice) facilitates estimation of the thickness of the Arctic and Southern Ocean sea ice covers. The smaller lidar footprint, higher height precision, and pulse repetition rate selected for ATLAS stem from lessons learned in the use of ICESat data (lower resolution and sample spacing) for freeboard retrieval. For understanding changes in geostrophic circulation, the altimetry of sea surface heights in open leads at high polar latitudes, not available from traditional open ocean altimeters (e.g., TOPEX/Poseidon), adds to observations of the time-varying sea surface from on-orbit polar orbiting platforms (e.g., CryoSat-2) within the ice-covered ocean. Photon-counting altimetry also offers the opportunity for adaptive sampling of the surface at variable length scales for improved resolution of surface roughness. Hence, IS-2 sea ice products have a unique character compared to altimetry from traditional approaches.

IS-2 sea ice heights have been assessed from the Airborne Topographic Mapper (ATM) lidar (1 m diameter footprint) in four dedicated Operation IceBridge under-flights during the 2019 Arctic deployment (Figure 1 shows one such comparison). From the near-coincident retrievals, in a mix of seasonal and older ice, we found remarkable correlations (averages

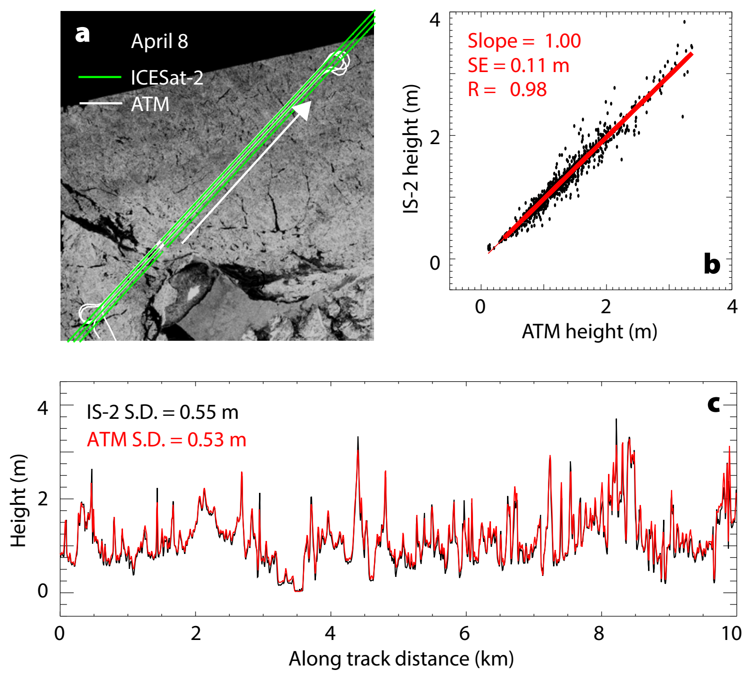

FIGURE 1. Comparison of ICESat-2 (IS-2) heights with a 10 km surface profile acquired by the ATM lidar (on Operation IceBridge) on April 8, 2019. The profiles are centered at ~80.5°N, ~100 km north of the Sverdrup Islands. The regression slope, standard difference, and correlation of the two profiles are shown in (b).

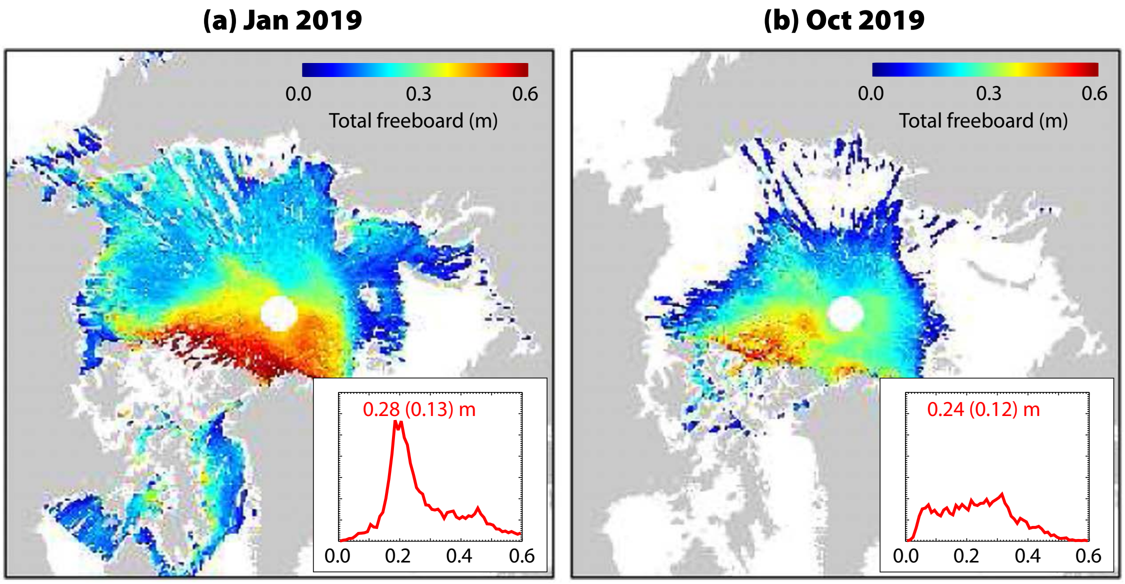

FIGURE 2. Two examples of monthly Arctic sea ice freeboard composites from ICESat-2 products (ATL10 and ATL20) for the months of January and October 2019. The retrieved freeboards are plotted on a 25 km x 25 km grid.

to > 0.95) and near-unity regression slopes. Even with potential mis-registrations between profiles due to location and ice drift residuals, the results indicate close agreement of the height estimates. Larger differences between the surface heights are seen in rougher areas where it is more difficult for the photon heights to capture the surface distributions at short length scales. Differences in total freeboard in available 10 km segments show a variability of 0.02 m to 0.04 m.

Over the ice-covered oceans, retrieved surface heights and total freeboards from the multiple ATLAS beams are provided in high resolutions (tens of meters) along-track (product designation: ATL07 and ATL10) and in gridded monthly composites of sea ice freeboard (ATL20) and sea surface height anomalies (ATL21). These sea ice and ocean products are available through the National Snow and Ice Data Center (https://nsidc.org/data/icesat-2). Two sample freeboard composites and distributions (Figure 2) from IS-2 sea ice products show the range of freeboard and spatial character of the Arctic ice cover in midwinter and early fall. Current investigations by the IS-2 science team have focused on (to name but a few): in-depth assessment of these products; variability of ice thickness from different approaches used to estimate snow loading, surface roughness, behavior of freeboard, and thickness in summer; retrieval of melt-pond coverage and depth during melt; the impact of waves in freeboard determination; the compactness of the ice cover; and floe size distributions. With progress in understanding ATLAS acquisitions, numerous efforts to introduce new value-added products (e.g., snow depth) and novel uses of photon-counting altimetry for sea ice and other disciplines are being explored (e.g., blowing snow over the ice cover, uses of sub-surface returns). A list of IS-2 related publications on recent scientific results are available at https://icesat-2.gsfc.nasa.gov/publications.

As of December 2021, ICESat-2 had completed its three-year prime mission and is currently in extended operation. The nonstop operations (with only a few short interruptions) have provided all season coverage of the polar oceans. The ATLAS instrument remains healthy and is using its primary laser (the first of two), and the spacecraft has sufficient fuel to last through at least early 2030.

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SIDEBAR > ICE MASS BALANCE BUOYS

By Don Perovich

Satellite observations show that the sea ice cover in the Arctic is in decline. Ice extent is decreasing in all months of the year, and the ice is thinning and becoming younger. However, the observations do not delineate the details of how these changes are occurring. In situ measurements of sea ice mass balance can determine the amount of ice growth and the amount of ice surface melt and ice bottom melt. During field experiments, ice mass balance observations are straightforward using instruments as simple as ablation stakes and thickness gauges. However, field experiments are limited in number, location, and time. Autonomous ice mass balance buoys can overcome these constraints and provide long-term measurements at multiple sites.

There are a few different types of autonomous ice mass balance buoys and sensor packages. Buoys may be designed for multiyear or seasonal ice, and they are all equipped to determine geographic location, track the position of the surface and the ice bottom, transmit observations via satellite, and measure internal ice. The data collected provide time series of snow accumulation and melt, ice growth, surface ice melt, and bottom ice melt. Ice mass balance buoys are typically designed with open architecture that permits additional sensors, including acoustic rangefinders, barometers, radiometers, strain gauges, anemometers, and conductivity cells.

FIGURE 1. Photo of a Seasonal Ice Mass Balance (SIMB) buoy deployed in the Arctic. *Photo credit: Ryleigh Moore*

The Snow and Ice Mass Balance Array (SIMBA) buoy is one example. It has a 4.8 m long digital temperature string at 0.02 m spacing (Liao et al., 2018). It also has a heating element on the back of each temperature sensor that provides a pulse of heat whose decay is measured by the temperature sensor. The decay time is used to determine the thermal diffusivity of the medium, thus resolving whether the sensor is in air, snow, ice, or water. SIMBAs also carry a GPS, a barometer, and an Iridium transmitter.

The Seasonal Ice Mass Balance (SIMB) buoy can be used in either multiyear or seasonal ice (**Figure 1**). It is a 0.12 m diameter, 4.9 m long spar buoy designed to float in open water (Planck et al., 2019). It consists of two acoustic rangefinders, one above the ice looking down in order to track surface position, and one in the ocean looking up to track ice bottom position. It has a 3.8 m long digital temperature chain with sensors placed every 0.02 m. There are also a GPS, a barometer, and a shielded air temperature sensor. Data are transmitted via Iridium, and the measurement sampling interval is user selectable. The buoy has a battery life of 1.5 to 2 years.

Figure 2 plots results of barometric pressure, air temperature, ice growth rate, snow depth, ice temperature and thickness, surface melt, and bottom melt from an SIMB deployed in the Central Arctic. The buoy was deployed in October 2019, and the floe broke up in late July 2020. The barometric pressure panel shows changes due to synoptic weather events that are evident in high-frequency changes in air temperature, which are superposed over the low-frequency seasonal cycle. The central panel illustrates the ice mass balance, with the gray shaded area showing the accumulation and melt of the snow cover. The red/purple interface is the bottom of the ice. Changes in air temperature propagate partially into the ice as shown by the color contours of ice temperature. The initial ice thickness of 0.80 m increased to 1.90 m by the end of the growth season in late May. The peak ice growth rate of 0.75 cm day^{-1} occurred in December. Melt onset and the total amount of melt were similar for surface melt (June 9, 0.31 m) and bottom melt (June 11, 0.30 cm).

The full utility of ice mass balance buoys is achieved when they are collocated with other autonomous systems that observe the atmosphere and ocean as part of a network.

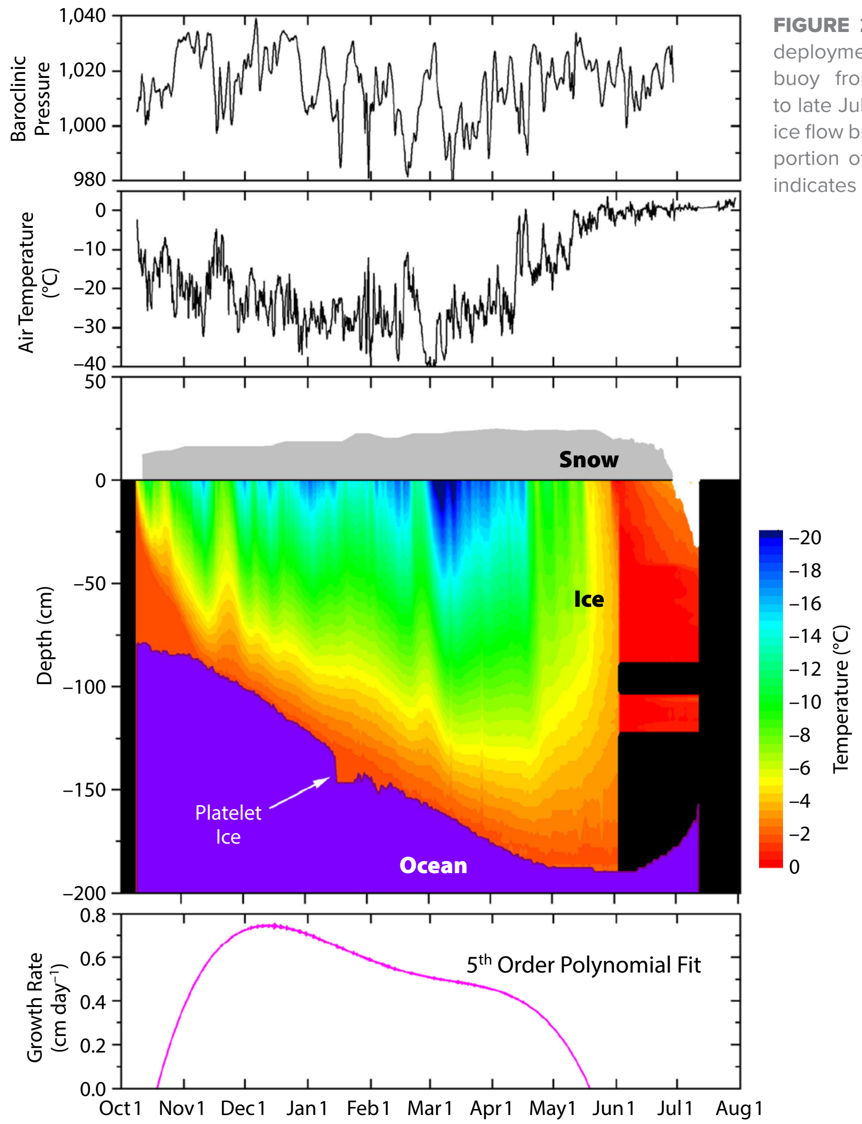

FIGURE 2. Results from a deployment of the SIMB buoy from October 2019 to late July 2020, when the ice flow broke up. The black portion of the contour plot indicates missing data.

Ideally, these systems are deployed at multiple locations and over multiple years, allowing atmosphere-ice-ocean processes to be studied and spatial and temporal trends to be explored. For example, results from autonomous networks in the Beaufort Sea have investigated the interannual variability of the melt season and the increased ocean contribution to ice loss (Planck et al., 2020). The Sustainable Arctic Observing Network and the International Arctic Buoy Program are international efforts to deploy more autonomous systems in the Arctic Ocean.

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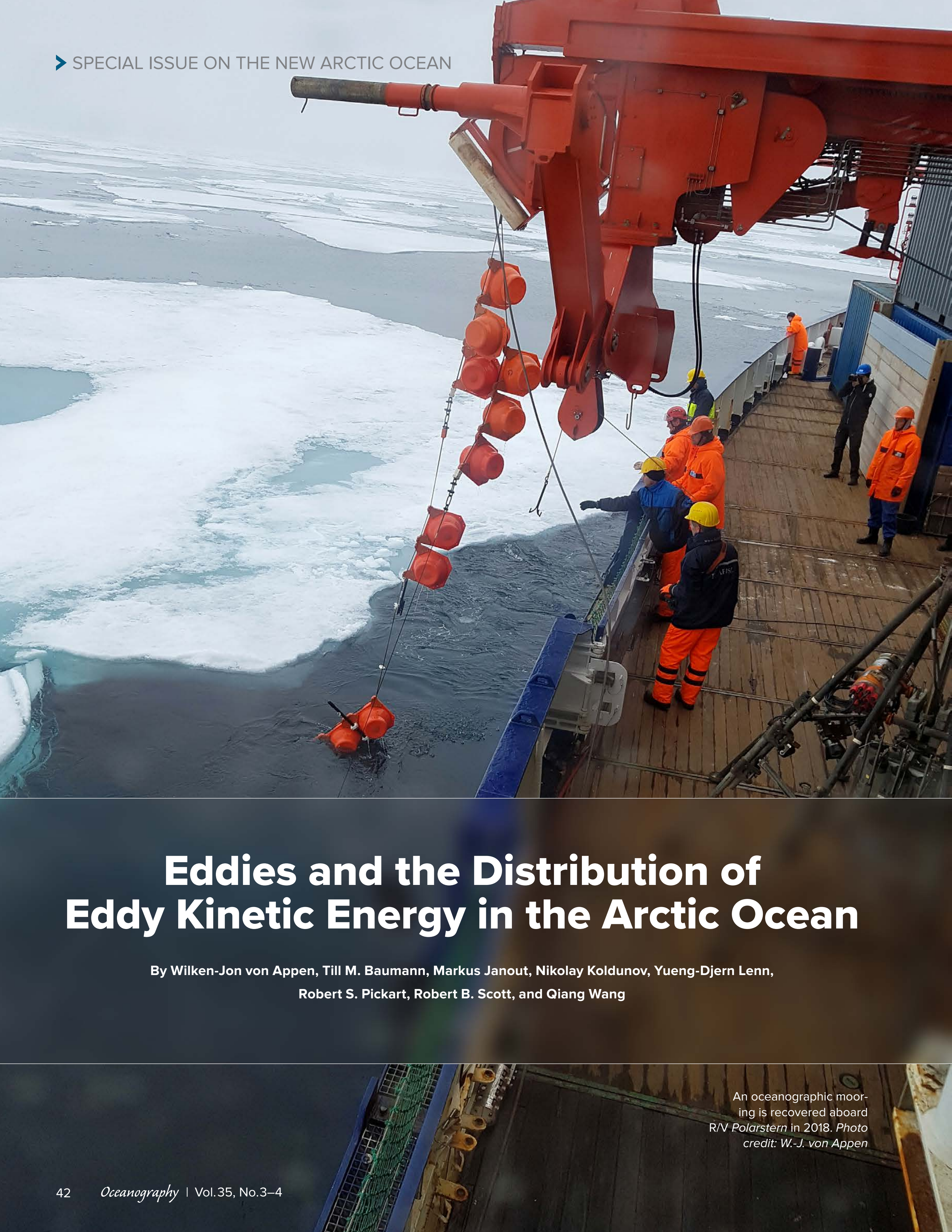


Eddies and the Distribution of Eddy Kinetic Energy in the Arctic Ocean

By Wilken-Jon von Appen, Till M. Baumann, Markus Janout, Nikolay Koldunov, Yueng-Djern Lenn, Robert S. Pickart, Robert B. Scott, and Qiang Wang

An oceanographic mooring is recovered aboard R/V *Polarstern* in 2018. *Photo credit: W.-J. von Appen*

ABSTRACT. Mesoscale eddies are important to many aspects of the dynamics of the Arctic Ocean. Among others, they maintain the halocline and interact with the Atlantic Water circumpolar boundary current through lateral eddy fluxes and shelf-basin exchanges. Mesoscale eddies are also important for transporting biological material and for modifying sea ice distribution. Here, we review what is known about eddies and their impacts in the Arctic Ocean in the context of rapid climate change. Eddy kinetic energy (EKE) is a proxy for mesoscale variability in the ocean due to eddies. We present the first quantification of EKE from moored observations across the entire Arctic Ocean and compare those results to output from an eddy resolving numerical model. We show that EKE is largest in the northern Nordic Seas/Fram Strait and it is also elevated along the shelf break of the Arctic Circumpolar Boundary Current, especially in the Beaufort Sea. In the central basins, EKE is 100–1,000 times lower. Generally, EKE is stronger when sea ice concentration is low versus times of dense ice cover. As sea ice declines, we anticipate that areas in the Arctic Ocean where conditions typical of the North Atlantic and North Pacific prevail will increase. We conclude that the future Arctic Ocean will feature more energetic mesoscale variability.

INTRODUCTION: EDDIES IN THE ARCTIC OCEAN

During the second half of the twentieth century, physical oceanographers increasingly appreciated that the world ocean is populated by eddies (Warren and Wunsch, 1981) and that they are fundamental to setting ocean stratification and to understanding the dynamics of the global circulation (e.g., Gnanadesikan, 1999). These swirling water motions are the main form of mesoscale variability. The timescales over which these features evolve typically range from a few days to a few months. As the name suggests, the mesoscale ranges from small-scale local effects of tides, individual storms, and mixing on the fast end to large-scale basin-wide circulation on the slow end of the spectrum.

It is more difficult to study eddies in the Arctic Ocean than in lower latitudes, and research addressing them in the Arctic increased significantly only in the past two decades after four major challenges were overcome. First, sea ice cover and harsh weather make the Arctic particularly inaccessible for in situ observations. Second, while lower latitude eddies are observed to have typical horizontal scales of hundreds of kilometers, high latitudes are associated with very small Rossby radii (the typical horizontal scale of eddies) on the order of 1–15 km (Nurser and Bacon, 2014), requiring observations and numerical models to have very high horizontal resolution. Third, satellite remote-sensing products, which have been instrumental for mesoscale research at lower latitudes for decades, are of less value in the Arctic. For instance, sea ice disturbs typical satellite measurements at the sea surface, the prevailing near-freezing temperatures make eddy detection based on sea surface temperature impractical, and the small Rossby radius necessitates high horizontal resolution. In addition, many polar-orbiting satellites have inclinations <75° thereby missing the majority of the Arctic Ocean, although the recent CryoSat mission has improved on this limitation. Fourth, many Arctic eddies exist as subsurface lenses that are obscured from surface observations (e.g., Porter et al., 2020).

Here, we review examples from which insights have been gained on the character and ubiquity of Arctic eddies. These studies are based on ship-based surveys, bottom-moored and ice-based observations, and regional and/or process numerical models designed to overcome the challenges specific to the Arctic Ocean. The eddies are similar in size to the Rossby radius and are the dominant form of mesoscale variability. However, we note that distinguishing eddies from inertial oscillations and tidal variability remains a challenge as the frequencies in question can be very close (Lenn et al., 2021).

The high-resolution (1 km) numerical model of Wang et al. (2020) resolves most eddies. A snapshot of speed from the model (Figure 1a) shows that strong velocities (>0.3 m s^{-1}) are present in parts of the Arctic Ocean. For example, in Fram Strait it shows small (~30 km diameter) energetic vortices that are formed via baroclinic instability where Atlantic Water recirculates and subducts below Polar Water (Hattermann et al., 2016). These prominent and well-delineated eddies (Johannessen et al., 1987; Figure 2a) are characterized by relatively strong motions of up to 0.5 m s^{-1} (Figure 1b,c; von Appen et al., 2016). We consider this an illustrative example of energetic circulation at the boundaries and contrast it with the dynamically much quieter interior basins, such as the Nansen Basin, with water speeds of <0.05 m s^{-1} (Figure 1b,c).

Baroclinic and barotropic instability of the northward-flowing West Spitsbergen Current on the eastern side of Fram Strait produces eddies, especially in winter when the boundary current is weakly stratified (von Appen et al., 2016, and references therein). The transfer rate of mean potential energy to eddy energy (i.e., baroclinic conversion with units of W m^{-3}) in this region has been estimated from observations (von Appen et al., 2016), and models show it to be higher than in most other regions of the Arctic (Wang et al., 2020). Tracking simulated eddies reveals that their lifetimes are on average 10 days in Fram Strait (Wekerle et al., 2020).

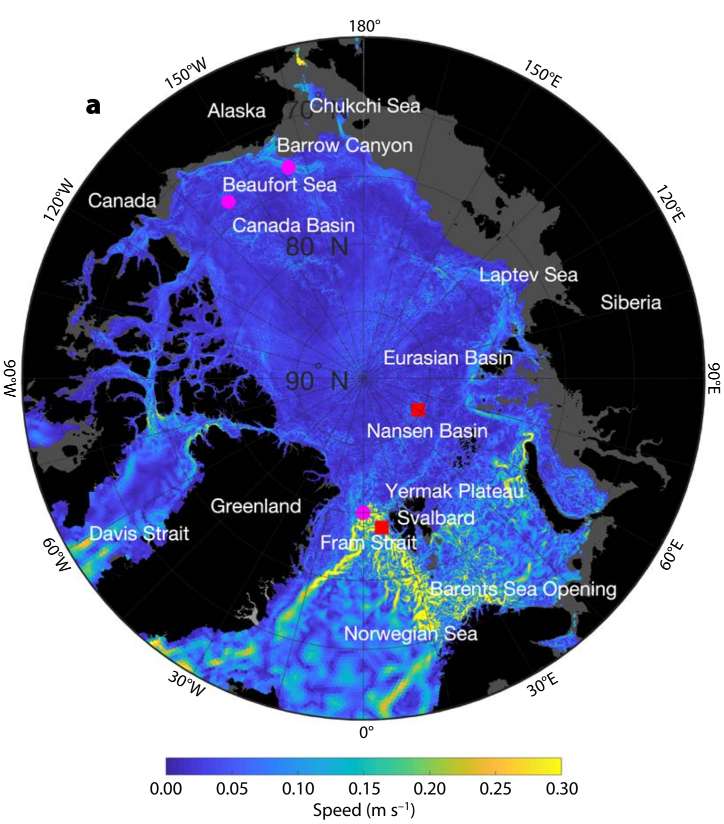
It is enlightening to consider different locations along the cyclonic Arctic Circumpolar Boundary Current (Aksenov et al., 2011). Northeast of Svalbard (near 30°E), Våge et al. (2016) showed a 25 km diameter mid-depth intensified anticyclonic (clockwise rotating in the Northern Hemisphere) eddy of Atlantic Water. This eddy highlights a likely mechanism of export of Atlantic Water and an associated heat flux to the Nansen Basin from the boundary current (Renner et al., 2018).

North of the Laptev Sea (near 125°E), mooring observations have shown eddies within and offshore of the boundary current with approximately one eddy per month passing this location (Pnyushkov et al., 2018). Some of the eddies have likely been advected from the western Nansen Basin or even from Fram Strait, while others may have formed from local baroclinic instability (Pnyushkov et al., 2018). Model simulations indicate that the continental slope region in the eastern Eurasian Basin features higher conversion from available potential energy to eddy kinetic energy than the interior of the Arctic basin (Wang et al., 2020).

Warm Pacific Water, which is lower in salinity and thus lighter than Atlantic Water, enters the Arctic Ocean from Bering Strait and crosses the shallow Chukchi Sea shelf. Upon exiting Barrow Canyon at the northeast edge of the shelf, it forms the eastward-flowing Western Arctic Shelfbreak Current north of Alaska (Pickart, 2004) as well as the westward-flowing Chukchi Slope Current north of the Chukchi Sea (Corlett and Pickart, 2017). Farther to the west, Pacific Water exiting Herald Canyon forms the eastward-flowing Chukchi Shelfbreak Current (Linders et al., 2017). Small (10–20 km diameter) anticyclonic eddies containing Pacific Water in their cores are commonly found in the Canada Basin (Manley and Hunkins, 1985, and Fine et al., 2018, and references therein) though at numbers much smaller than near the boundaries. These anticyclones are readily formed from the shelfbreak currents of the Chukchi and Beaufort Seas (e.g., Pickart et al., 2005; Scott et al., 2019; Figure 2b). The Western Arctic Shelfbreak Current was found to be baroclinically unstable (Spall et al., 2008; von Appen and Pickart, 2012), with mooring-based baroclinic conversion rates near 152°W on the Beaufort slope varying seasonally with magnitudes close to those of Fram Strait.

The role of synoptic wind forcing as a source of mesoscale variability, in addition to eddies, was also studied extensively from the Beaufort slope array. It was found that atmosphere-to-ocean momentum transfer is more effective at intermediate (10%–70%) sea ice concentrations than in more consolidated pack ice or open water (Schulze and Pickart, 2012). On synoptic timescales, upwelling-favorable winds can bring relatively warm and nutrient-rich Atlantic Water across the shelf break and onto the shelf (Pickart et al., 2013). Conversely, downwelling-favorable winds are able to flush water that is rich in resuspended matter from the bottom boundary layer off the shelf (Dmitrenko et al., 2018; Foukal et al., 2019).

Most of the mooring measurements and ship-based observational studies in the Arctic are focused on the boundary currents. By contrast, knowledge of the variability in the deep basins is largely based on Ice-Tethered Profilers (ITPs). ITP surveys in the southern Canada Basin found significantly more anticyclonic than cyclonic eddies (e.g., Zhao et al., 2014). Normally, cyclones and anticyclones occur in roughly similar numbers in the ocean. The deviation from this pattern in the Beaufort Sea has been linked to the fact that cyclones tend to occur at the surface, while anticyclones are generally subsurface features. The associated surface velocities presumably lead to a relatively strong ice-ocean drag that spins down the cyclones without



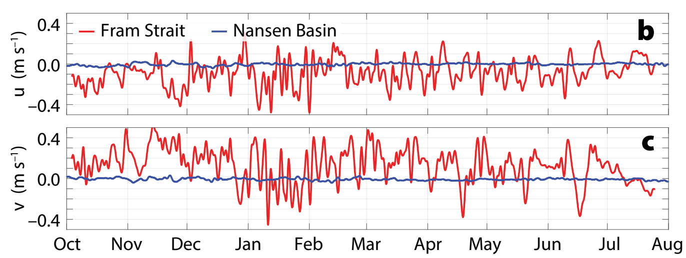


FIGURE 1. (a) Snapshot of current speed averaged over 50–100 m from 1 km numerical simulation of Wang et al. (2020) on December 30, 2008. Note that the 1 km resolution region of the model starts at approximately 75°N in the Nordic Seas. Place names are labeled in white and indicate locations close to the bottom left of each label. Magenta dots mark the locations of the studies shown in Figure 2. For illustrative purposes, two time series of velocity are presented, one representative of very high and one of very low mesoscale variability: (b) eastward velocity [m s^{-1}] and (c) northward velocity [m s^{-1}] at mooring F4 in Fram Strait and mooring Nansen in the Nansen Basin, both marked by red squares in (a). The velocities are averaged over 50–100 m and lowpass filtered with a two-day cutoff. F4, at 78°50'N 7°E in 1,416 m water depth, and Nansen, at 85°18'N 60°E in 3,870 m water depth, have average eddy kinetic energies of 1.3*10^{-2} m^2 s^{-2} and 6.7*10^{-5} m^2 s^{-2}, respectively.

a comparable effect on anticyclones (Chao and Shaw, 1996).

Zhao and Timmermans (2015) identified three types of eddies in the Canada Basin: shallow eddies, mid-depth double core eddies, and deep eddies (**Figure 2c** shows an example of a shallow eddy). The radii of observed eddies tend to be centered at 7 km and 4 km in the Canada Basin and 4.5 km in the Eurasian sector of the Arctic Ocean (Zhao et al., 2014). These eddy length-scale estimates are in agreement with the comparatively smaller Rossby radius in the Eurasian Basin due to weaker stratification in the same depth range. Timmermans et al. (2008) proposed that some of the Beaufort Gyre eddies are produced from baroclinic instability of an upper ocean front near 78°N. Carpenter and Timmermans (2012) showed deep-reaching (>1,500 m) eddies in the weakly stratified Atlantic Water and deep water layers, while Bebieva and Timmermans (2019) identified the effects of eddies on double diffusion.

The studies discussed above provide a view of some of the Arctic Ocean observational programs that address mesoscale variability. The different programs are generally focused on specific geographical regions, depending on accessibility and national and institutional research priorities. They provide an incomplete view of Arctic mesoscale dynamics and activity. For an integral pan-Arctic view, we rely on information from numerical models, in particular from those with the sufficiently fine grids, on the order of ~1 km, that are needed to resolve most mesoscale processes in the deep Arctic Ocean. However, a quantitative evaluation of the models' abilities to realistically reproduce the relevant processes as they occur in the ocean is important and requires comparison of metrics extracted from both models and observations. One such dynamically relevant parameter is eddy kinetic energy (EKE), which provides a measure of eddy activity and can readily be computed from both observations and numerical models. We provide an overview of mesoscale activity in the Arctic Ocean based on one such high-resolution numerical simulation and a compilation of mooring records collected over the past few decades by the international science community.

DATA AND METHODS

We use two previously compiled comprehensive mooring current meter/acoustic Doppler current profiler (ADCP) databases (https://www.nature.com/articles/s41597-020-00578-z/tables/3 and http://mespages.univ-brest.fr/~scott/GMACMD/gmacmd.html) that have been employed in past studies of tides (Baumann et al., 2020) and lee wave generation (Wright et al., 2014). We complemented these collections with more recent records as well as multiyear time series (as listed in a table at Pangaea; see von Appen et al., 2022) to more extensively investigate the temporal and spatial trends and variability in mesoscale activity.

We interpolated the depth-averaged eastward and northward velocities (u, v) to hourly values from 1980 to 2020. This was done separately for the depth ranges 50–100 m and 500–1,000 m, which roughly correspond to the halocline (upper Atlantic Water layer in western Eurasian Basin) and lower Atlantic Water/deep water layer, respectively, across most of the Arctic Ocean. In ice-covered waters, moorings cannot contain surface buoys, and upward-looking ADCPs cannot measure closer to the surface than 8% of their distance from the surface. Hence, no surface and near-surface observations exist. From the model (see below), we estimate that, on average, near-surface EKE values are 1.3 times larger than the 50–100 m

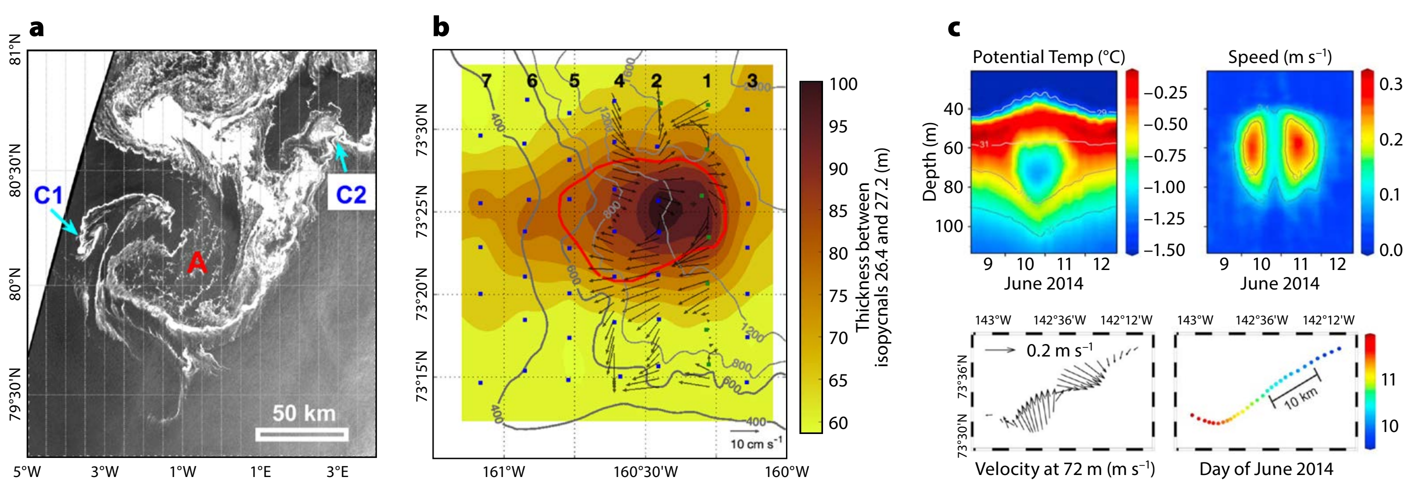


FIGURE 2. Examples from the literature show observations of eddies in the Arctic Ocean. (a) Synthetic aperture radar image of an anticyclone (A) and two cyclones (C1, C2) in the marginal ice zone of Fram Strait. White indicates sea ice, and dark gray indicates open water. (b) Map view of a shipboard hydrographic survey of an eddy of Pacific Water north of the Chukchi Sea. Color shows the thickness in m of the layer between the 26.4 kg m^{-3} and 27.2 kg m^{-3} isopycnals, and vectors show velocities from the vessel-mounted ADCP (scale vector in bottom right). (c) Time series of an eddy in the Canada Basin measured by an Ice-Tethered Profiler drifting over a typical upper halocline eddy. Top two panels show temperature/speed transects; bottom two panels provide map views of horizontal velocity/measurement date. *(a) From Kozlov et al. (2020). (b) From Scott et al. (2019). (c) From Zhao et al. (2016), reprinted with permission from Wiley. The formatting of the x- and y-axis labels in (a) and (b) has been changed from the original.*

average. We only considered observations over topography deeper than 50 m, given that mesoscale dynamics are fundamentally different on the shallow continental shelves. Redeployment locations in different years may vary by up to a few kilometers for operational reasons; hence, we clustered observations within 3 km of one another and considered them as a single mooring time series. In total, we have 212 deployment locations with an average duration of 2.4 years (ranging from 2 months to 18 years).

The quantities (u_{mean}, v_{mean}) are the velocities averaged over the full duration of the record. We then filtered the (u,v) with a fourth-order Butterworth filter to obtain: (u_{lp}, v_{lp}) = lowpass filtered with 30 day period cutoff, (u_{bp}, v_{bp}) = bandpass filtered with 2-day to 30-day cutoffs, and (u_{hp}, v_{hp}) = highpass filtered with 2-day cutoff. The 2-day cutoff is chosen to exclude tidal motions and inertial oscillations and the 30-day cutoff is chosen to exclude seasonal and interannual variability (comparable to, e.g., von Appen et al., 2016); hence, (u_{bp}, v_{bp}) allow us to concentrate on the mesoscale variability in the 2- to 30-day band. Data gaps smaller than the periods used for filtering were interpolated linearly, while larger data gaps were retained as missing values. We define the mean kinetic energy (MKE), low-frequency kinetic energy (LKE), eddy kinetic energy (EKE), and high-frequency kinetic energy (HKE) as

$$\text{MKE} = ½\,(u_{mean}^2 + v_{mean}^2),$$

$$\text{LKE} = ½\,\overline{(u_{lp}^2 + v_{lp}^2)},$$

$$\text{EKE} = ½\,\overline{(u_{bp}^2 + v_{bp}^2)},$$

$$\text{HKE} = ½\,\overline{(u_{hp}^2 + v_{hp}^2)},$$

where the mean is a temporal mean over the hourly values within, for example, a certain season or ice regime. In most cases, the sum of LKE, EKE, and HKE accounts for more than 90% of total kinetic energy (not shown). Kinetic energy in the ocean is a log-normally distributed quantity spanning many orders of magnitude, implying that the filtering does not artificially remove a lot of energy. We note that some eddies may have rotation-associated variability on periods longer than the bandpass cutoff. If these eddies translate through the domain, their signals may still be contained in the bandpass-filtered signal.

We also use a global simulation with the FESOM2 model that has a 1 km horizontal resolution in the Arctic Ocean (i.e., >75°N in the Nordic Seas, >65°N in the Bering Sea; Wang et al., 2020). The model is forced with the JRA55 atmospheric reanalysis product (Tsujino et al., 2018). The online model calculation of EKE is defined slightly differently (a quantification of all variability with periods less than a month; see equation 1 of Wang et al., 2020). We use this alternate definition in Figure 3, while we apply the bandpass-filtered EKE definition to daily model output for year 2009 (the only year for which daily output was saved) to calculate Figure 4d. The model does not contain tides. Hence, the HKE in the model is small and, on average, the online calculated EKE is less than two times larger than the bandpass-filtered EKE (Pangaea table). For a log-normally distributed quantity such as EKE, this constitutes good agreement. The third type of data we use is Advanced Microwave Scanning Radiometer (AMSR) satellite-derived sea-ice concentration provided at https://seaice.uni-bremen.de/sea-ice-concentration/amsre-amsr2/ (Spreen et al., 2008), which ranges in time from 2002 to 2021.

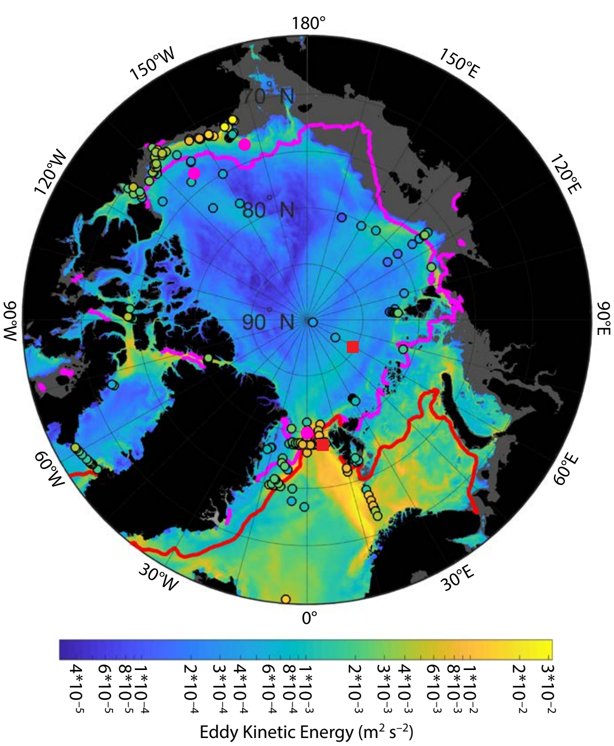


FIGURE 3. Map of 50–100 m eddy kinetic energy (EKE) [$m^2\,s^{-2}$]. Values calculated from all available mooring records are shown as colored circles. Values corresponding to all variability with periods of less than 1 month taken from 1 km numerical simulation of Wang et al. (2020) are shown in the background. Note that moorings in very close spatial proximity partially overplot. A log10 scale is applied to the color bar. The 2002–2019 February (red) and August (magenta) mean sea ice edges (20% concentration) are also shown. Note that the summer ice edge has been located further north in the last decade. Land is shown in black and the shelves (model bathymetry <100 m depth) in dark gray.

REGIONAL HOTSPOTS AND TEMPORAL VARIATION OF MESOSCALE VARIABILITY IN THE ARCTIC OCEAN

We present the 50–100 m averaged EKE calculated from all available mooring records as colored circles in Figure 3. The background color shows the numerical model-derived EKE of Wang et al. (2020). Consistent with the literature described above, our results identify the Beaufort shelf break, the Arctic Circumpolar Boundary Current, the western part of the Norwegian Sea, Barents Sea Opening, Fram Strait, and, to a lesser extent, the Yermak Plateau as hotspots of mesoscale variability. By comparison, the interior Canada Basin and, to a lesser extent, the Eurasian Basin are quiescent. These interior basin regions still contain eddies, but, as the EKE indicates, they are weaker (less energetic) and less frequent than in regions with higher EKE. EKE in the most energetic regions is almost 1,000 times larger than in the most quiescent regions. Note that this may also be affected by the fact that in the Atlantic inflow regions, the low stratification means that EKE in the 50–100 m depth range may be similar to (near-) surface variability, while in other regions with stronger stratification, there may be a steeper decline of the variability from the surface downward.

We now explore differences in the EKE (Figure 4) and try to explain some of them. EKE in the 50–100 m depth range is 1.5–10 times higher than EKE in the 500–1,000 m depth range (Figure 4a). Observations of 50–100 m EKE over topography shallower than 1,000 m are about an order of magnitude larger than EKE over topography deeper than 3,000 m (Pangaea table). In the Atlantic Water inflow regions (Barents Sea Opening, Fram Strait, western Nansen Basin), EKE in winter is 2–10 times higher than in summer (Figure 4b) and fall (Pangaea table). Presumably, the lack of dense ice covers in the inflow regions allows for the stronger atmospheric forcing in winter to drive mesoscale-band variability in the ocean directly. Additionally, baroclinic instability associated with convection may drive mesoscale-band variability in parts of the inflow regions. This is different along the eastern Siberian shelves and the Beaufort Sea where summer atmospheric forcing in ice-free conditions probably leads to stronger EKE, though the winter-summer change is smaller than in the Atlantic inflow regions. Along the Alaskan slope, EKE is largest in fall (Pangaea table) when storm activity intensifies but full ice cover is not yet developed, consistent with the peak in momentum transfer from the atmosphere to the ocean under intermediate sea ice concentrations (Schulze and Pickart, 2012).

Sea ice cover leads to a reduction by a factor of 1.5–4 in EKE in most regions (Figure 4c) except for the parts of Fram and Davis Straits where sea ice cover is infrequent and its presence presumably represents especially strong flow events from the Arctic. The numerical model matches the observations well to within one order of magnitude (Figure 4d), with an average underestimation of slightly less than a factor of 2 (Pangaea table). However, the model predicts weaker variability in the western Arctic than observed.

EKE is larger (often by up to a factor of 10) than mean kinetic energy in most parts of the Arctic Ocean except for the Nansen Basin (Pangaea table). EKE accounts for up to half of total kinetic energy in the Beaufort Sea, while its share is smaller elsewhere (Pangaea table). However, low frequency kinetic energy, which includes seasonal and interannual variability, is 2–8 times larger than EKE in the boundary current north of Siberia and up to 2.5 times smaller than EKE along the western Beaufort slope (Figure 4e).

With regard to temporal change, the observations are limited, and most locations show differences between the decades 2000–2010 and 2010–2020 that are much less than the differences described above (Figure 4f). Fram Strait appears to show a small increase (~10%) in EKE, potentially linked to decreasing ice cover. Conversely, the eastern Arctic slope along Eurasia and the Beaufort slope regions show a small decrease by ~20%. This is counterintuitive, as an increase in the strength of the cyclonic boundary current has been observed in the eastern Eurasian Basin (Polyakov

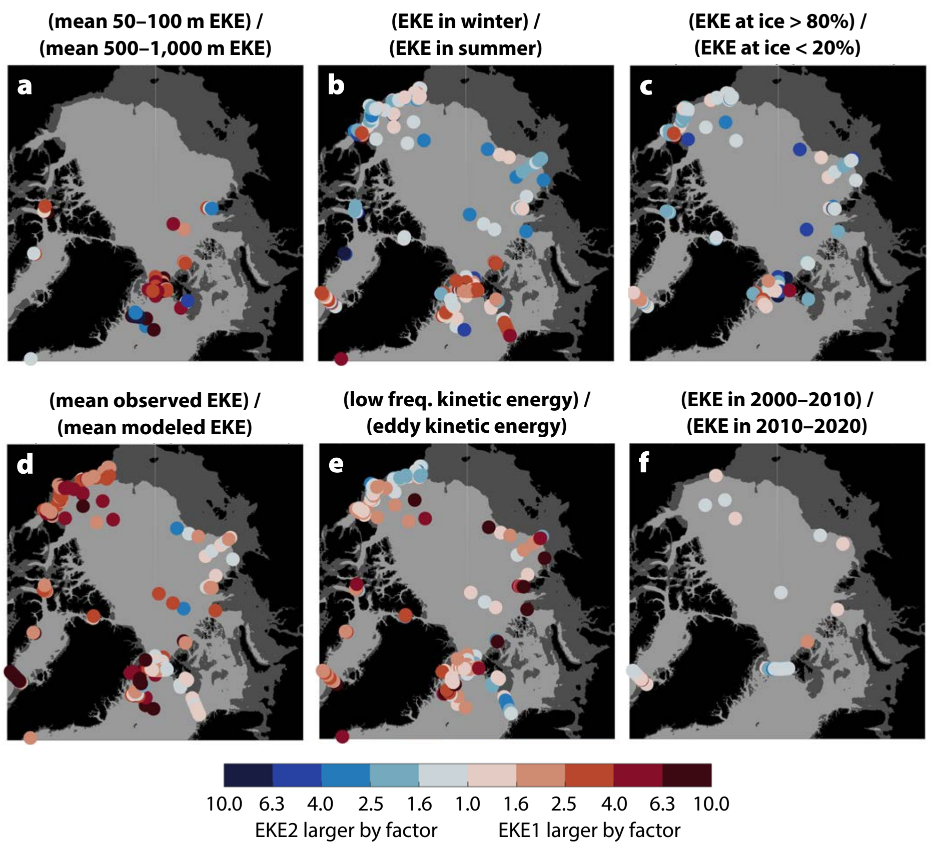


FIGURE 4. Maps of EKE ratios (EKE1/EKE2). (a) Shallow (50–100 m average) EKE divided by deep (500–1,000 m average) EKE. (b) Winter (January/February/March) EKE divided by summer (July/August/September) EKE. (c) Ice-covered EKE (>80% sea ice concentration at closest Advanced Microwave Scanning Radiometer (AMSR) grid point to the mooring location) divided by open water EKE (<20% sea-ice concentration). (d) Mooring-observed EKE divided by modeled EKE (Wang et al., 2020); here the model EKE is calculated from bandpass filtered daily mean time series in 2009. (e) Low-frequency kinetic energy (LKE) divided by EKE. The low-frequency (30-day lowpass filtered) kinetic energy includes seasonal and interannual variability. (f) EKE during 2000–2010 divided by EKE during 2010–2020. Except for (a), all EKEs are averages over 50–100 m. Land is shown in black, the shelves (<200 m depth) in dark gray, and the deep ocean (>200 m depth) in light gray; bathymetry is from IBCAOv3.

et al., 2020), which can be partially attributed to Arctic sea ice decline (Wang et al., 2019b). Note, however, that interdecadal changes may also be influenced by changes in the measurement configuration of long-term observations, especially due to the instrument type used and the vertical location and range of the measurements; hence, these conclusions should be considered tentative.

IMPACTS OF MESOSCALE VARIABILITY ON ARCTIC OCEAN CIRCULATION, SEA ICE, AND BIOLOGICAL PRODUCTION

The mesoscale eddy field drives and/or affects a number of important processes in the Arctic. As boundary currents flow along the shelf break, they become baroclinically and/or barotropically unstable. The instabilities can result in the formation of eddies containing fluid from the boundary current, which thereby can flux mass and momentum into the basin (Spall et al., 2008). The associated loss of potential and kinetic energy suggests that the Western Arctic shelfbreak current will spin down over ~150 km in summer and ~1,400 km in winter (von Appen and Pickart, 2012). Also, in Fram Strait, the West Spitsbergen Current appears to lose mass offshore through eddy transport, mostly of Atlantic Water (von Appen et al., 2016), which feeds the recirculation in the strait (Hattermann et al., 2016).

The model of Nøst and Isachsen (2003) explains the Atlantic Water circulation as flow along f/H contours (where f is the Coriolis frequency and H is the water depth) that is due to the forcing associated with the integral of the wind component parallel to f/H contours. Conversely, the model of Spall (2013) provides a plausible way of explaining the cause for the Atlantic Water circulation: the horizontal eddy fluxes of salt from the Atlantic Water boundary current balance the vertical diffusion across the halocline. This sets the halocline depth, which in turn determines the boundary current velocity through thermal wind. In a warming climate with decreased ice cover and therefore more mechanical energy input from the atmosphere to the ocean, the vertical diffusion is expected to increase, resulting in a deeper halocline. Increased eddy generation would ensue from this additional available potential energy, and, through thermal wind, the Atlantic Water boundary current would increase in strength (Spall, 2013).

The Beaufort Gyre is a wind-driven, anticyclonic circulation that stores a substantial amount of freshwater (i.e., water with a lower salinity than, for instance, Atlantic Water). The wind-driven Ekman downwelling in the center of the Beaufort Gyre results in inclined isopycnals. These become baroclinically unstable, forming mesoscale eddies that counteract the downwelling through a residual mean circulation (Manucharyan and Spall, 2016; Meneghello et al., 2021). Recent studies suggest that changes in the wind-driven Beaufort Gyre strength are counteracted by the joint effect of ice-ocean stress coupling and mesoscale eddies (Meneghello et al., 2018; Wang et al., 2019a). As sea ice has retreated over the past two decades in the Canada Basin, additional wind energy has been input to the ocean, resulting in an increase in eddy activity in the Beaufort Gyre (Armitage et al., 2020).

Additionally, because they are intermittent, eddies lead to variations in water masses and the strength of stratification. Such changes impact horizontal and vertical mixing and can influence the amount of heat fluxed vertically across the halocline and available to melt sea ice. They can also alter the vertical nutrient flux necessary to sustain primary production (MacKinnon et al., 2021), as well as provide energy sources that locally increase turbulence.

Eddies modulate primary production and vertical carbon export from the productive layer in the Arctic Ocean in various ways. If eddies are not resolved explicitly (e.g., Schourup-Kristensen et al., 2018) their biogeochemical effects in ocean general circulation biogeochemistry models of the Arctic need to be parameterized, which is difficult in the absence of a complete knowledge of the relevant processes. Under-ice primary production is a key contributor to the total primary production in the Arctic Ocean (Jin et al., 2015). Because eddies can modulate sea ice concentration and distribution (see below), they may have a nonlinear effect on primary production in the Arctic Ocean. Unlike eddy permitting models, low resolution ocean biogeochemistry models fail to reproduce features such as the low surface nutrient concentrations in the Canada Basin (Jin et al., 2018), suggesting that eddies may be an important mechanism for establishing nutrient distribution. Watanabe et al. (2014) argued that shelfbreak mesoscale eddies are vital in transporting biomass from the wide Arctic shelves to the deep basins where it can be sequestered by sinking (i.e., the biological carbon pump). Likewise, eddies can carry resuspended matter from the shelves to the basins, e.g., in eastern Fram Strait (Koenig et al., 2018).

Several dedicated field (as well as numerical modeling) programs designed to study the differences in ecology and biogeochemistry inside and outside of mesoscale eddies in lower latitudes have been carried out over recent decades. Among other findings, this has led to the conclusion that anticyclones (cyclones) with downwelling (upwelling) in their centers typically exhibit less (more) primary production than surrounding waters. The number of similar studies in the Arctic is small (e.g., Llinás et al., 2009; O'Brien et al., 2013; Nishino et al., 2018, and references therein) largely because of the logistical challenges of working in ice-covered waters, the short phytoplankton growth season, and the small eddy scales of several kilometers.

Consolidated sea ice dampens eddy kinetic energy by reducing the atmosphere-ocean momentum transfer that drives part of the mesoscale variability, for example, along Arctic shelf breaks (Figure 4c). Conversely, in the marginal ice zone, the atmosphere to ocean momentum transfer changes with the presence/absence of sea ice. Thus, strong sea ice concentration gradients may represent an approximate step change in regions experiencing heat loss and wind mixing (both enhanced on the open water side). This may also set up density fronts in the upper ocean that become unstable and form mesoscale (and submesoscale) eddies.

Detection of eddies from space is largely limited in the Arctic Ocean by the presence of sea ice and the eddies' small scales. In the open water, however, satellite altimetry can be used to detect large eddies (Kubryakov et al., 2021). Von Appen et al. (2016) demonstrated that along-track altimetry data can be used in the non-ice-covered ocean to obtain EKE estimates consistent with mooring-based estimates. Sea ice, especially at low to intermediate concentrations (i.e., in the marginal ice zone), acts as an approximate passive surface tracer similar to biofilms/oil and surface drifters. Hence, satellites may show narrow streaks of high sea ice concentration that enable us to visualize surface divergence and strain fields. These signatures can be readily detected by satellite synthetic aperture radar (SAR; e.g., Figure 2a). From sequential images, surface velocity (Kozlov et al., 2020) and vorticity (Cassianides et al., 2021) can be inferred. These SAR signatures have been used to guide in situ sampling campaigns targeting mesoscale eddies (e.g., Johannessen et al., 1987) and submesoscale fronts (von Appen et al., 2018) in the marginal ice zone. The differential advection of sea ice by the mesoscale flow field in the marginal ice zone may impact regional sea ice melt and formation rates by either exposing or sheltering sea ice from warm ocean water (Horvat et al., 2016).

CONCLUDING REMARKS

Based on the insights presented above, we can speculate about how mesoscale variability might change in the future Arctic Ocean with progressing sea ice decline and Atlantification (Polyakov et al., 2017; and see sidebar by Pnyushkov and Polyakov, 2022, in this issue). Areas that are ice-free in winter, or have low ice concentrations, are associated with large EKE in winter (Figure 4b), suggesting that a decrease in winter sea ice extent in a warming climate may facilitate more eddy generation. This change may particularly apply to the continental slopes, which are now often subject to summertime melt. For example, the eddy formation mechanism of Timmermans et al. (2008) requires winds blowing parallel to a frontal jet (resulting in jet acceleration and subsequent destabilization). Such a mechanism is much more likely to occur in low ice conditions. Spin-up of the boundary current will also be associated with an increase in available potential energy and thus baroclinic instability. All these mechanisms would lead to more eddies in the Arctic Ocean.

Other interesting investigations that could be based on the mooring records used here include calculation of the number of individual eddies passing by each of the mooring sites and detection of mesoscale variability in the accompanying temperature records. It would also be worthwhile to investigate more carefully the lifetimes of eddies in different locations, and, considering their translation speeds, how far they propagate through the Arctic Ocean. The curvature of topographic corners along isobaths, in combination with the inertia in boundary currents, is predestined to lead to eddy shedding. Hence, the relation between the curvature of the topography and the frequency of eddies and the EKE could also be investigated to determine, among other things, their basin-wide relevance. These investigations might uncover important aspects of Arctic Ocean eddies that are presently unknown.

Finally, additional studies will help to improve our understanding of present and future mesoscale variability in the Arctic Ocean, especially in the central basins, including its effect on physical-biological coupling and sea ice. Field efforts should include observations with moorings and ice-based platforms and also make use of the novel under-ice capabilities of gliders and Argo floats. Whenever possible, these should be done in tandem with idealized and/or realistic high-resolution numerical modeling.

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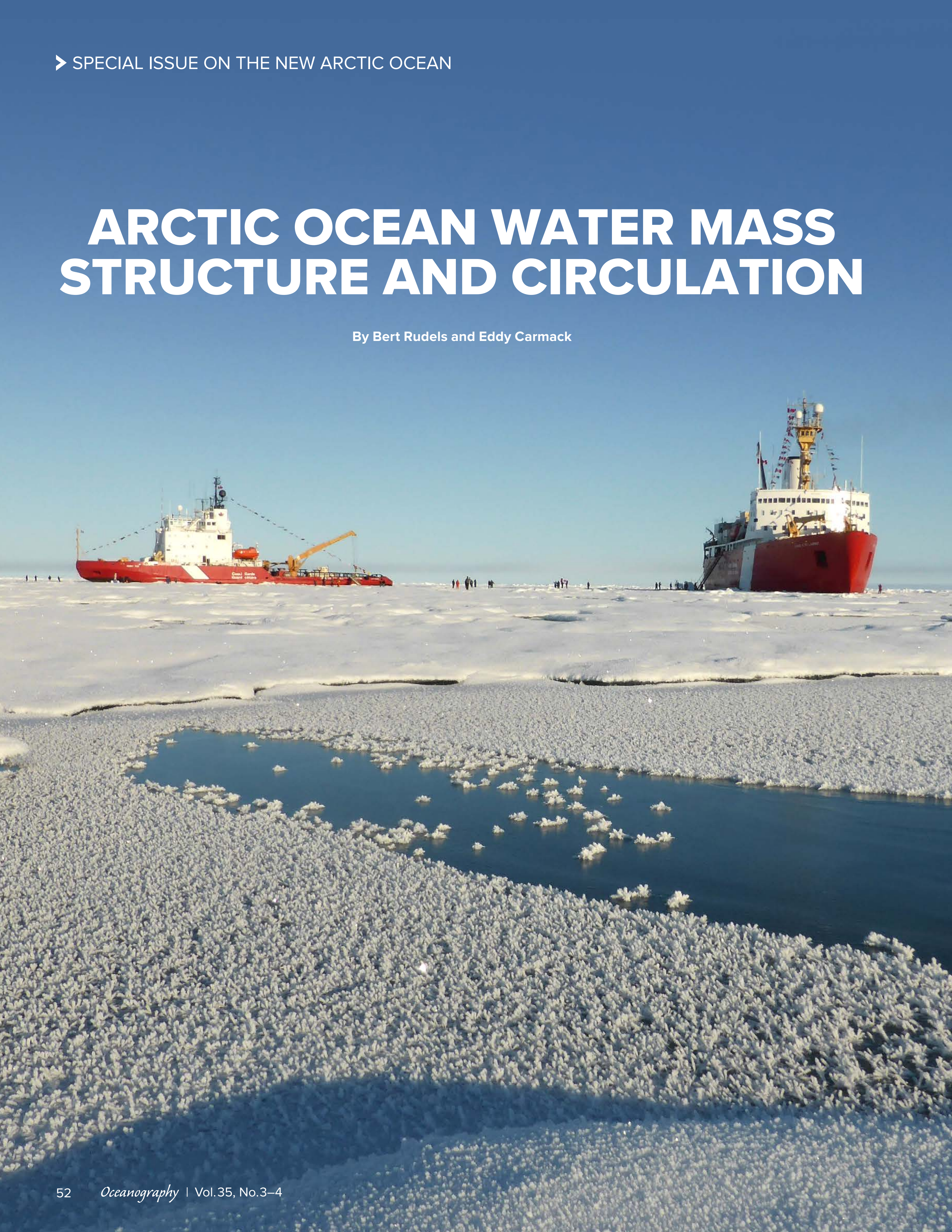
ARCTIC OCEAN WATER MASS STRUCTURE AND CIRCULATION

By Bert Rudels and Eddy Carmack



ABSTRACT. The Arctic Ocean is the smallest of the world oceans, yet one whose currents and water masses extend globally. It is an advection-dominated ocean in that currents import distinct waters from both the North Atlantic and the North Pacific that interact and layer vertically by density. Further modified by river inputs and the freezing and melting of sea ice, the Arctic Ocean exports modified waters back into the North Atlantic, thus impacting the global thermohaline circulation. This physical system forms the backdrop for almost all chemical, biological, and geological processes within the Arctic Ocean, all of which are expected to change in a warming Earth. To anticipate the effects of such changes in external and advective forcing, it is necessary to understand how they interact and are manifested in the observed hydrographic structures. The aim of this review is thus to present and discuss the processes responsible for these structures.

INTRODUCTION AND SETTING

In 1990, the German oceanographer Detlef Quadfasel went as tourist on a cruise on the Soviet icebreaker *Rossiya* to the North Pole, taking with him expendable temperature probes. He discovered that the temperature of the mid-depth Atlantic layer was more than one degree above that reported from previous measurements (Quadfasel et al., 1991). This observation drastically changed the focus from determining the mean circulation and water mass structure to detecting and documenting change. Subsequent expeditions in the following decade revealed changes also in water mass structure (Steele and Boyd, 1998; Morison et al., 1998), frontal zone locations (Carmack et al., 1995), currents, and response to atmospheric forcing (Maslowski et al., 2000). A comparison of submarine upward-looking sonar tracks of the ice cover 30 years apart showed that the ice cover thickness had been reduced by almost half (Rothrock et al., 1999). Gone was the concept of a steady state ocean, and to detect, study, and understand change became a major goal of Arctic research.

Many of the observed changes were advective, related to the inflow of Atlantic and Pacific waters as well as to the warming climate. The northward advection of warmer air, containing more clouds and water vapor, increases the downward longwave radiation that causes higher surface temperatures (Mortin et al., 2018), and the inflow of warmer Atlantic water provides more heat to the upper layer beneath the ice (Polyakov et al., 2012a). Rivers flowing north from the massive, surrounding continental drainage basins add a third advective component. All these transports affect the ice cover, causing melting or inhibiting freezing.

The Arctic Ocean's polar-centric location means that it is affected seasonally by the most variable radiative forcing of all oceans: during the polar night, the air temperature may sink below –40°C, and the continuous daylight at summer solstice provides more shortwave radiation at the top of the atmosphere than that received at the equator. It is mostly a β ocean, that is, strongly stratified in salinity but not always in temperature. Winter cooling is thus confined to a strongly stratified and relatively shallow surface layer, allowing the surface to reach freezing temperature and form sea ice. The local, oceanic heat given up to the atmosphere and to space is then latent heat of freezing, not sensible heat stored in the water column, and the overlying atmosphere becomes colder than it otherwise would be. In summer, the ice cover reflects a substantial fraction of the incoming shortwave solar radiation, and the melting ice keeps the surface temperature close to freezing, thus making the summer cooler than expected, considering the many hours of sunlight the Arctic Ocean receives during this season.

The Arctic Ocean is also unique among global oceans in that its shelves comprise approximately 50% of its area, so seasonal modifications of water masses are amplified. With mean depths ranging from 200 m to less than 50 m, the shelves are geographically separated into the Barents, Kara, Laptev, East Siberian, and Chukchi Seas north of the Eurasian continent, and the Beaufort Sea, Lincoln Sea, and Canadian Arctic Archipelago north of North America. The deep part of the Arctic Ocean consists of two major basins, the Eurasian and Amerasian Basins, which are physically separated by the Lomonosov Ridge with a mean depth of 1,600 m and a sill depth of 1,870 m. The Eurasian Basin is further divided by the Gakkel Ridge into the 4,500 m deep (the average depth of the abyssal plain) Amundsen Basin and the 4,000 m deep Nansen Basin, and the Mendeleev Ridge and the Alpha Ridge system separate the Amerasian Basin into the smaller 4,000 m deep Makarov Basin and the larger 3,800 m deep Canada Basin (Figure 1a).

CIRCULATION AND STRATIFICATION: FROM THE BOTTOM UP

The advective flows into the Arctic Ocean have long been recognized. In the mid-nineteenth century, the possibility that these warm inflows could influence the ice cover and create open water in the interior of the Arctic Ocean was seriously discussed (Petermann, 1865; Bent, 1872). Fridtjof Nansen's drift with *Fram* demonstrated that this was not the case, but instead a warm layer with temperatures above 0°C was present between 150 m and 600 m depth, showing that warm Atlantic water does enter the Arctic Ocean; however, it is separated from the sea surface by a low salinity upper layer that prevents its heat from reaching the ice (Nansen, 1902).

This strong, permanent stability is created by the global-scale atmospheric transfer of water vapor from lower to

PREVIOUS PAGE. Canadian icebreakers CCGS *Louis S. St-Laurent* (right) and CCGS *Terry Fox* (left) at the North Pole, August 24, 2015. *Photo credit: Jane Eert, Fisheries and Oceans Canada* higher latitudes, and in the Arctic Ocean the local net precipitation is augmented by its large continental catchment areas, which deliver over 10% of the global river runoff. The Arctic Ocean becomes a β (salt-stratified) ocean (Carmack, 2007), and the resulting stability isolates the underlying water column from surface forcing so that it is dominated by advection. Exchanges between the upper and the deep ocean are only possible via the shallow shelves and the upper slope, or by inputs from adjacent seas.

That sea ice formation on the shelves could be important for the ventilation of the deeper layers of the Arctic Ocean was first argued by Nansen, ironically based on erroneous salinity determinations from the *Fram* expedition, which showed that the salinity of the deep waters was higher than that of Atlantic water. He suggested that freezing and brine rejection on the shelves could explain these high salinities. However, Nansen later suggested, based on Amundsen's *Gjøa* observations in 1901, a role for the deep open ocean convection occurring in the Greenland Sea, and he eventually accepted the possibility that the deep and bottom water in the Arctic Ocean originated in the Greenland Sea (Nansen, 1906, 1915).

This description of the deep circulation in the Arctic Ocean and the Nordic Seas, elaborated with more observations by Wüst (1941), was accepted for more than 50 years. When Worthington (1953) found that the temperatures below 1,300 m were lower in the eastern (Eurasian) half than in the western (Amerasian) half of the Arctic Ocean, he concluded that a submarine ridge must divide the Arctic Ocean in two basins, preventing the coldest, densest water from the Greenland Sea from reaching the western Arctic Ocean. This ridge, the Lomonosov Ridge, had, unknown to Worthington, been detected by Soviet scientists in 1948. It was not until Aagaard (1980) pointed out that the Amerasian Basin deep water was not only warmer but also more saline than the Eurasian Basin deep water that Nansen's shelf source suggestion was considered anew (Aagaard et al., 1981, 1985; Rudels, 1986). It is now accepted that the deep circulation in the Arctic Ocean and in the Nordic Seas forms a tightly linked system, with the Arctic Ocean shelves providing the warm/saline and the Nordic Seas the colder/fresher end members.

The deep and bottom water masses in the Arctic Ocean's four deep basins each have their own distinct characteristics. The coldest bottom water occurs in the deepest basin, the Amundsen, with a potential temperature of −0.94°C and salinity around 34.943. The bottom water in the shallower Nansen Basin is slightly warmer but less saline, while the bottom water in the Canada basin is clearly

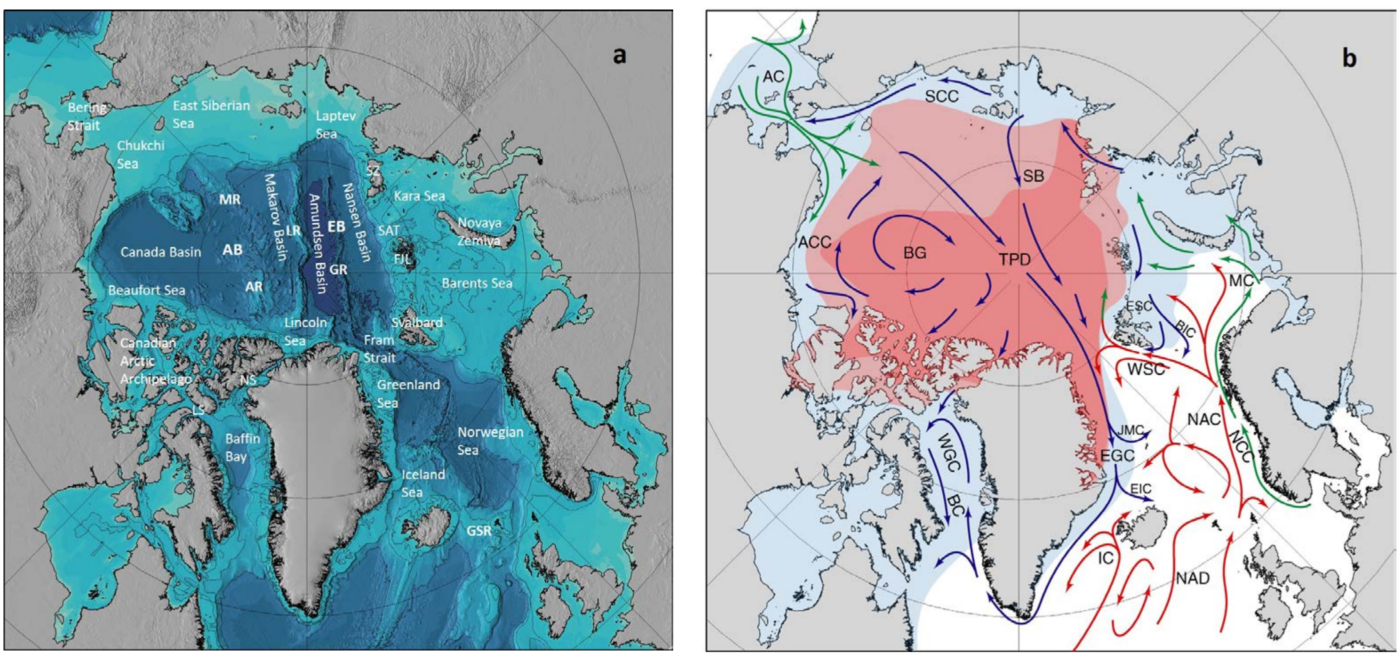


FIGURE 1. (a) Arctic Ocean bathymetry from the international bathymetric chart of the Arctic Ocean updated database (Jakobsson et al., 2008). The projection is Lambert Equal Area and the 200 m, 500 m, 2,000 m, and 4,000 m isobaths are shown. *Adapted from Rudels et al. (2012). Map drawn by Martin Jakobsson*. AB = Amerasian Basin. AR = Alpha Ridge. EB = Eurasian Basin. FJL = Franz Josef Land. GR = Gakkel Ridge. GSR = Greenland-Scotland Ridge. LR = Lomonosov Ridge. LS = Lancaster Sound. MR = Mendeleev Ridge. NS = Nares Strait. SZ = Severnaya Zemlya. (b) The circulation of the upper layers of the Arctic Ocean. Warm Atlantic currents are indicated by red arrows, cold less saline polar and Arctic currents by blue arrows. Low salinity transformed currents are indicated by green arrows. The annual mean maximum ice extent is shown in blue and the annual minimum in red (late twentieth century conditions). The minimum in 2007, the second absolute minimum to date, is shown in dark red. AC = Anadyr Current. ACC = Alaskan Coastal Current. BC = Baffin Island Current. BIC = Bear Island Current. BG = Beaufort Gyre. EGS = East Greenland Current. EIC = East Iceland Current. ESC = East Spitsbergen Current. IC = Irminger Current. JMC = Jan Mayen Current. MC = Murman Current. NAD = North Atlantic Drift. NAC = Norwegian Atlantic Current. NCC = Norwegian Coastal Current. SB = Siberian branch (of the Transpolar Drift). SCC = Siberian Coastal Current. TPD = Transpolar Drift. WGC = West Greenland Current. WSC =West Spitsbergen Current. *From Rudels et al. (2012)*

warmer, −0.551°C, and more saline, 34.958. The vertical structures of the deep waters in these three basins are similar. Temperature decreases and salinity increases down to about 1,000 m from the bottom, where the temperature starts to increase with depth, creating a deep temperature minimum. The temperature and salinity increase until a thick homogeneous bottom layer, capped by a thermohaline step structure, is reached; these layers are 1,000 m thick in the Canada Basin and about 600 m in the Amundsen Basin and 500 m in the Nansen Basin (Figure 2).

The temperature and salinity increase toward the bottom can be explained by shelf/slope convection. The inflow through Fram Strait comprises warm, saline Atlantic water and less saline and colder intermediate and deep water, and the slope convection entrains Atlantic water and becomes warmer. If it is saline enough, it sinks into and increases the temperature and salinity of the advected intermediate water below (Quadfasel et al., 1988).

The deep temperature minimum in the Canada Basin is likely due to spreading of colder water from the Makarov Basin across the Mendeleev Ridge (see profiles in Figure 2). The minima in the Amundsen and Nansen Basins are located deeper than the sill in Fram Strait, have no obvious advective sources, and are more difficult to explain. The temperature of the sinking plumes, once they have passed the Atlantic water, cannot be increased by entrainment, except intermittently, if the salinity and temperature of the inflow change with time. However, the thick, homogeneous bottom layers suggest that geothermal heating could lead to temperature increases, convection, and homogenization of the bottom water (Timmermans et al., 2003; Björk and Winsor, 2006). Observations of the bottom layer in the Canada Basin during the first decade of the twenty-first century indicate that the bottom temperature has increased, supporting the idea of geothermal heating (Carmack et al., 2012).

The structure in the deep Makarov Basin is different. No deep temperature minimum is present, and the salinity reaches its maximum value 1,000 m above the bottom and then remains constant with depth, while the temperature continues to decrease until it forms a 700 m thick bottom layer (Profiles in Figure 2). Jones et al. (1995) suggested that the absence of a temperature minimum was due to spillover of colder intermediate depth water from the Amundsen Basin across the sill in the central Lomonosov Ridge. This water would, due to the thermobaric effect (see later section on Internal Mixing Processes), sink to the bottom and cool the deep water in the Makarov Basin. Later observations (Björk et al., 2007), however, did not confirm such overflow. If it is the cause of the temperature structure in the deep Makarov Basin, the overflow must be intermittent (Rudels, 2012).

CONNECTIONS WITH THE WORLD OCEAN

The largest exchanges between the Arctic Ocean and the rest of the world ocean occur in the North Atlantic. There, warm Atlantic water crosses the Greenland-Scotland Ridge and enters the Nordic Seas (the Greenland, Iceland, and Norwegian Seas), which form a large anteroom for the two Atlantic entrances to the Arctic Ocean, the shallow (200 m) Barents Sea and the deep (2,600 m) Fram Strait. The Atlantic water flows north in the Norwegian Atlantic Current, where strong heat loss to the atmosphere leads to cooling and densification of the entering water. The current splits north of Norway, and a substantial fraction enters the Barents Sea, which makes the southern part of the Barents Sea ice-free throughout the year. The remainder of

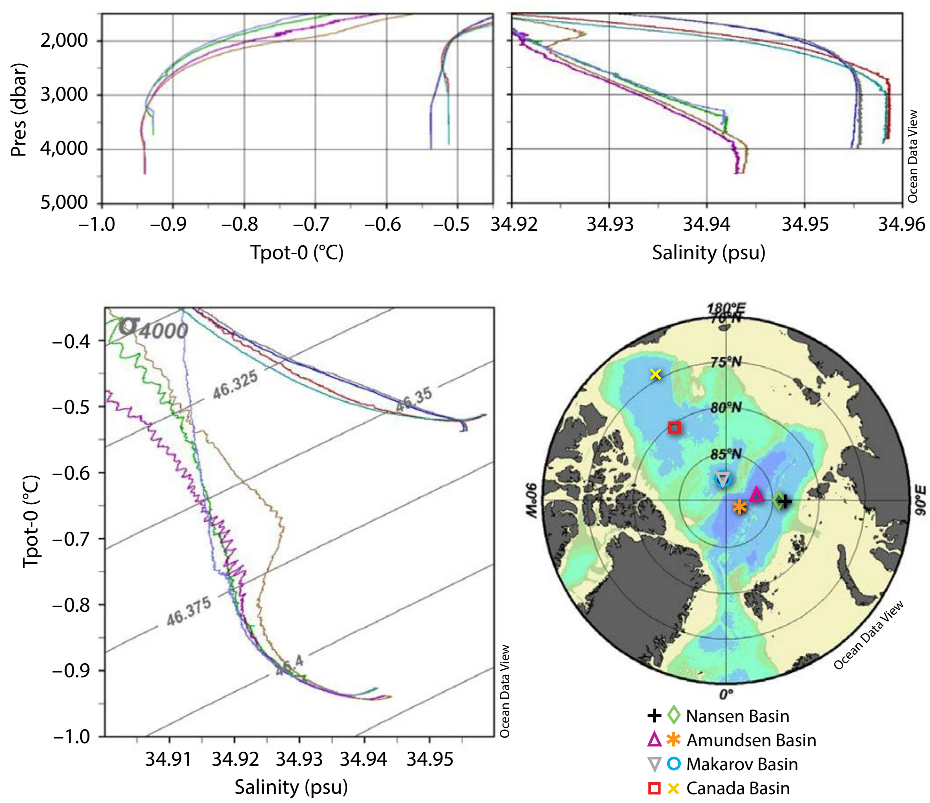


FIGURE 2. Deep and bottom water characteristics from the Nansen, Amundsen, Makarov, and Canada Basins. Green = Nansen Basin (diamond on map). Purple = Amundsen Basin (triangle). Gold = Makarov Basin (asterisk). Red = Canada Basin (square). Green = Canada Basin (x). Note the absence of a deep temperature minimum in the Makarov Basin and that the temperature minimum in the Canada Basin could be caused by an inflow at sill depth from the Makarov Basin. The deep (2,000 m) salinity maximum in the Amundsen Basin is likely caused by Makarov Basin deep water crossing the Lomonosov Ridge. The temperature minima in the Nansen and Amundsen Basins have no obvious advective sources but could be caused by intermittent inflow of colder water via the St. Anna Trough or by varying characteristics of the Fram Strait inflow branch. *From Rudels (2012)*

the Norwegian Atlantic Current continues as the West Spitsbergen Current to Fram Strait, where about half enters the Arctic Ocean and forms a boundary current that follows the Eurasian continental slope eastward. The rest recirculates in the strait and joins the southward-flowing East Greenland Current (Rudels, 1987; Figure 1b).

The Fram Strait inflow branch encounters and melts sea ice north of Svalbard, and its upper part is transformed into a less saline surface layer. The underlying warm "Atlantic" core becomes isolated, and its transfer of heat to the atmosphere is reduced. Rudels et al. (2004) assumed that the upper layer is created by sea ice melting and wind mixing and that the heat loss of the Atlantic water is distributed between the atmosphere and sea ice in such a way that the amount of sea ice melting is a minimum. This is actually the distribution requiring the least energy input from the wind to turbulent mixing (Rudels, 2016). The Barents Sea branch, by contrast, does not meet sea ice until it reaches the northeast corner of the Barents Sea, where it continues into the Kara Sea between Franz Josef Land and Novaya Zemlya. The temperature of the Atlantic water in the Barents Sea is then lower than that of the Fram Strait branch, which leads to a smaller fraction of the heat loss going to ice melting, and the salinity decrease in the created upper layer is less than in the corresponding layer north of Svalbard (Rudels et al., 2004).

The Arctic Ocean is not a closed bay. Rather, it has a narrow (80 km) and shallow (50 m) backdoor, Bering Strait, to the opposite part of the world ocean, the North Pacific. The North Atlantic is weakly stratified in temperature (α ocean) and well ventilated, while the North Pacific is strongly stratified in salinity (β ocean) and poorly ventilated below its seasonal pycnocline. Its upper layer is less saline, partly due to transfer of water vapor from the Atlantic across the Isthmus of Panama (Weyl, 1968). This leads to higher sea level in the North Pacific compared to the North Atlantic, forcing a northward barotropic flow of low salinity water through Bering Strait into the Arctic Ocean (Stigebrandt, 1984). After transiting the Chukchi Sea, the flow interleaves around 75 m depth in summer and about 150 m in winter between the low salinity surface layer and the Atlantic waters below, augmenting the already strong upper layer stability.

Beyond the Nansen Basin, the upper layers in the deep ocean basins are dominated by freshwater input, either from rivers or from the Bering Strait inflow. Only in the Nansen Basin do direct interactions between sea ice and warm entering water create a less saline upper layer that leads to higher density and weaker stability there than elsewhere in the Arctic Ocean.

The entering waters become transformed within the Arctic Ocean and eventually leave to the North Atlantic either through the shallow straits and channels in the Canadian Arctic Archipelago, mainly through Lancaster Sound and Nares Strait, or through Fram Strait in the East Greenland Current. Most of the waters derived from the Pacific inflow pass through the Archipelago, while the East Greenland Current comprises waters drawn from the entire water column, low salinity upper waters that intermittently include Pacific water, cooled Arctic Atlantic water, and intermediate and deep waters from the different basins. These waters become modified and augmented by mixing with the Atlantic water recirculating in Fram Strait and with the water masses in the central Greenland and Iceland Seas before they cross the Greenland-Scotland Ridge, either as low salinity polar water in the East Greenland Current or as dense overflows passing through Denmark Strait or the Faroe Bank Channel into the deep North Atlantic.

CIRCULATION IN THE ARCTIC OCEAN: WIND FORCING

The Upper Layers

The circulation in the Arctic Ocean is forced mechanically by the wind and by density changes caused by cooling and heating, by freezing and melting, and by freshwater input. The wind-driven Ekman transport dominates in the surface layer. Sea ice and the uppermost layer are mainly driven directly by the wind, but also by the dynamical topography created by the spatially varying Ekman transports. The large-scale wind field over the Arctic Ocean forces a clockwise circulation in the Amerasian Basin, centered at the Beaufort Sea, and a counterclockwise circulation over the western Siberian shelf and the Nansen Basin along the tracks of the low-pressure systems arriving from the North Atlantic. At the boundary between the two wind systems, the counter-rotating winds drive the TransPolar Drift, carrying sea ice and low salinity water from both the eastern Siberian shelves and the Beaufort Gyre toward Fram Strait. As the TransPolar Drift approaches the strait, it splits, with some water returning to the Beaufort Gyre and the rest continuing through Fram Strait. During the transit across the Arctic Ocean, waters are exchanged between the two wind-driven circulation systems (Figure 1b).

The variability of the overall atmospheric circulation is often described by the Arctic Oscillation (AO) index (Thompson and Wallace, 1998). It is a measure of the strength of the Polar Vortex, and an AO+ indicates a strong, tight vortex and an anticlockwise driving of the upper layer and a reduced Beaufort Gyre. By contrast, in the AO– situation, the clockwise circulation is strong and the Beaufort Gyre expands, keeping most of the Pacific inflow in the Amerasian Basin (Steele et al., 2004). In the AO+ situation, the weakened Beaufort Gyre allows the anticlockwise circulation in the Eurasian Basin to extend farther east, and some of the Pacific inflow is carried directly into the Eurasian Basin to exit through Fram Strait (Steele et al., 2004). At the same time, deeper lying waters from the Eurasian Basin shelves are forced across the Lomonosov Ridge to eventually enter the Beaufort Gyre (Morison et al., 2012).

The Barotropic Wind-Driven Circulation

Below the low salinity upper layer, the stratification is weak, and the water columns appear to follow the depth contours. In both the Arctic Ocean and the Nordic Seas, the bathymetry forms closed f/H contours, where f is the Coriolis parameter and H the ocean depth. This allows geostrophic barotropic flows to circulate around the basins along the f/H contours (Nøst and Isachsen, 2003). The vorticity added by the large-scale wind field is transferred to the deeper part of the water column, where it is dissipated by frictional bottom torque. The wind fields over the Nordic Seas and over the Eurasian Basin are anticlockwise, and to remove the injected vorticity, the circulation must be anticlockwise, with the shallow water to the right, looking in the direction of the flow. This is the situation in most parts of the Arctic Mediterranean ("Mediterranean" because it is mostly enclosed by land), but in the Canada Basin, the clockwise wind field could induce a clockwise circulation with the shallow water to the left, which occasionally has been reported (Newton and Coachman, 1974; Karcher et al., 2007).

In a theoretical and laboratory study of a two-basin system, Nøst et al. (2008) found that an anticlockwise wind field in one basin, for example, in the Nordic Seas, would generate an anticlockwise flow along the f/H contours in both basins, while clockwise driving could maintain a clockwise flow in the directly driven basin but a clockwise flow extending to the non-forced basin would eventually go unstable. This implies that the deep barotropic circulation in the Arctic Ocean could be forced to follow the f/H contours around the Nordic Sea and the Arctic Ocean by an anticlockwise wind field acting only over the Nordic Sea, dissipating the added vorticity by bottom friction. This circulation model, however, does not consider the strong thermohaline forcing and the transformations of the waters that take place along their pathways in the Arctic Ocean.

CIRCULATION IN THE ARCTIC OCEAN: THERMOHALINE FORCING

The Arctic Ocean is a global-scale double estuary (Carmack and Wassmann, 2006) in that the density of the entering Atlantic water both increases and decreases, creating return flows in the upper layers as well as in the deep, as shown schematically in Figure 3. In the Norwegian Sea and in the southern Barents Sea the Atlantic water is cooled and its salinity decreases slightly due to net precipitation. It is still at the surface, but its density has increased sufficiently for it to enter the deep overturning loop. However, when the Atlantic water eventually encounters sea ice in the Arctic Ocean north and east of Fram Strait, it loses heat both to the atmosphere and to sea ice melting. The meltwater added to the upper part of the Atlantic water lowers its density more than it is raised by the simultaneous cooling, and some Atlantic water is shifted into the upper, estuarine loop. For the Fram Strait branch this occurs north of Svalbard. By contrast, in the Barents Sea the atmospheric cooling of the Atlantic water continues longer, as it does not encounter sea ice until it reaches the northeastern part of the sea. The Atlantic water is then colder, and the upper layer created by sea ice melting becomes less freshened and denser than the corresponding layer north of Svalbard, and it may remain in and contribute to the deep loop.

The main part of the Barents Sea inflow enters the deep Nansen Basin along the St. Anna Trough and sinks to and below 1,000 m feeding the deep loop (Schauer et al., 1997). The upper, freshened layer encounters and mixes with water from the Fram Strait branch that enters the St. Anna Trough, and together they form a second boundary stream that flows eastward along the upper part of the continental slope parallel to but inshore of the Fram Strait branch. In the eastern part of the Kara Sea and north of Severnaya Zemlya, the slope narrows and the upper stream moves down slope. The isopycnal mixing with the Fram Strait branch increases and thermohaline intrusions are formed, especially at the core of the Atlantic layer but also in the thermocline above and in the intermediate layers below. The density of the merged stream is high, and it remains in the deep circulation loop.

North of the Laptev Sea, the Atlantic water in the boundary current is then colder and less saline than it is farther west, but it has not lost any appreciable amount of heat (or salt) to the overlying waters. Instead, the colder, less

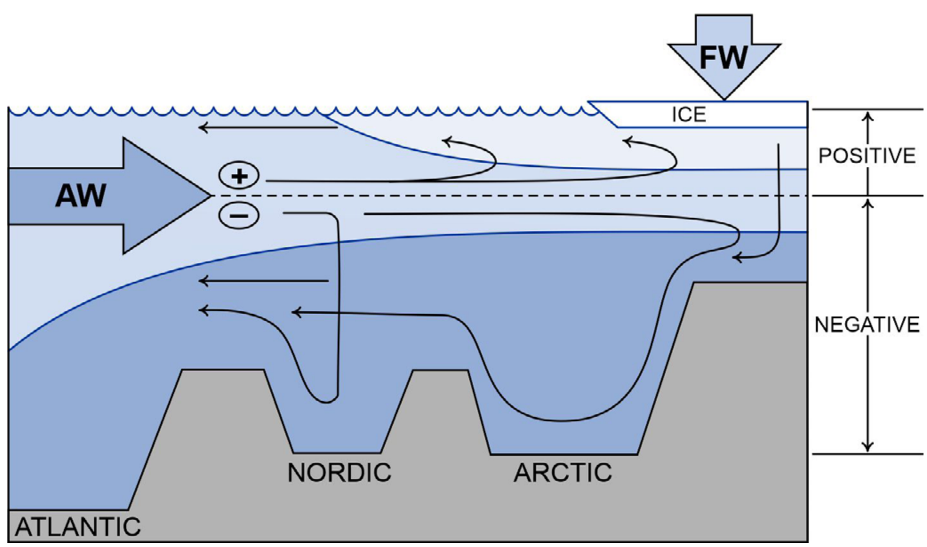


FIGURE 3. Schematic describing the estuary circulation. AW = Atlantic water. FW = freshwater. The sills in Fram Strait between the Arctic Ocean and the Nordic Seas and the Greenland-Scotland Ridge between the Nordic Seas and the North Atlantic are indicated. The plus sign indicates the formation of less dense water and the minus sign the formation of deep overflow water. *From Carmack and Wassmann (2006)*

saline upper slope stream, and possibly also other cold, saline contributions from the shelves, mix into the Atlantic layer, reducing its temperature and salinity. The heat has already been lost on the shelves. The Atlantic layer transport increases and its advected heat warms the added water, leading to lower mean temperatures. In recent years, however, Polyakov et al. (2019) have presented evidence that increased wind mixing and weakening stratification in the upper layers may induce increased vertical heat loss.

The water in the boundary current separates from the slope at prominent bathymetric features and enters the deep basins, where it forms gyres and loops that eventually rejoin the boundary current as it leaves the Arctic Ocean through Fram Strait. The water returning from the Nansen Basin is the warmest, while the recirculated water from the Amundsen, Makarov, and Canada Basins has become gradually colder (Figure 4).

The Norwegian Coastal Current, originating in the Baltic Sea and carrying runoff from there and from the Norwegian coast, moves north in the Norwegian Sea parallel to and shoreward of the Norwegian Atlantic Current and enters the Barents Sea (Figure 1b). Its continuations, the North Cape Current and the Murman Current, bring low salinity water farther along the Eurasian Coast to the Kara and Laptev Seas, where it is augmented by runoff from the large Siberian rivers, Ob, Yenisey, and Lena. In the eastern Laptev Sea this strong, low salinity coastal current splits. One part crosses the shelf break and enters the Amundsen Basin, flooding the boundary current and forming a low salinity layer above the upper layer advected from the Nansen Basin, which now becomes an intermediate water mass, a halocline, above the Atlantic core.

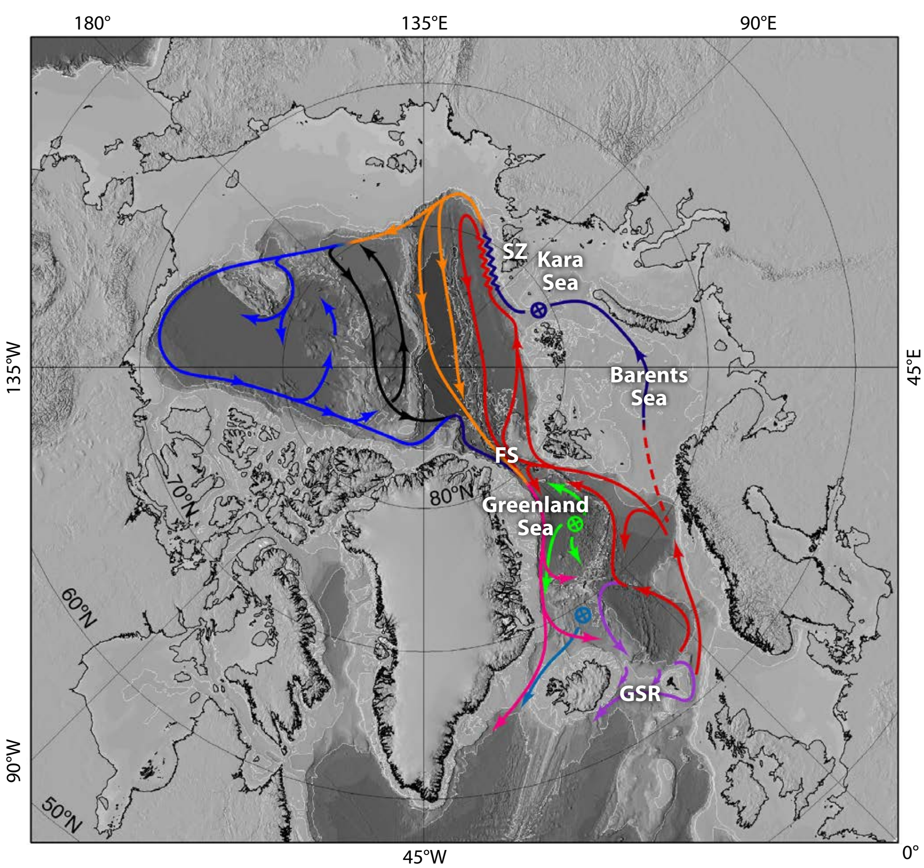


FIGURE 4. Schematic showing the circulation in the subsurface Atlantic Ocean and intermediate layers in the Arctic Ocean and the Nordic Seas. The interactions between the Barents Sea and the Fram Strait (FS) inflow branches north of the Kara Sea and Severnaya Zemlya (SZ) are indicated. The colors of the different loops show the gradual cooling of the Atlantic layer. The recirculation in Fram Strait and the intermediate water formation in the Greenland Sea are shown as well as the overflows across the Greenland-Scotland Ridge (GSR). *From Rudels et al. (2012)*

The low salinity shelf outflow directly enters the upper estuarine loop, and the shelf seas farther east, the East Siberian and Chukchi Seas, almost exclusively feed the upper loop. The waters on the shelves are supplied by river runoff and also by a more saline water mass that provides the saline mixing end member. From the Barents Sea to the Laptev Sea, this saline input derives from the Norwegian Coastal Current, while the Chukchi Sea and also the East Siberian Sea receive their saline end members from the Pacific inflow, even though the Pacific is a freshwater source for the Arctic Ocean as a whole.

Although the shelf contributions mainly feed the estuarine loop, they are influenced by the seasonal cycle. In winter, when the runoff is small, dense waters are created by brine rejection and accumulate at the bottom of the shelves to eventually cross the shelf break (Aagaard et al., 1981; see earlier section on Circulation and Stratification). These waters sink as dense boundary plumes that entrain intermediate water until they reach and merge with the basin water column at their appropriate density level. Less dense plumes feed the halocline and may also enter and cool the Atlantic layer. More saline plumes sink through the Atlantic core, entraining and transferring warm Atlantic water downward, adding both heat and salt to the intermediate and deeper layers. While the upper shelf outflows contribute to the estuarine mode, the bypassing plumes strengthen the overturning loop. The volume of entrained water is much larger than the initial volume sinking from the shelves, and the overturning loop becomes denser, more barotropic, and stronger. By contrast, the estuarine loop is only augmented by direct shelf outflow.

POLAR OUTFLOW AND DOUBLE ESTUARY EXCHANGES

The export of the less saline upper layer occurs through several passages, the narrow straits in the Canadian Arctic Archipelago and Fram Strait in the East

Greenland Current. The outflows have the coast to the right, and their widths are determined by the internal Rossby radius, the ratio of the internal longwave velocity to the Coriolis frequency, here about 10 km (Münchow and Melling, 2008; Rudels, 2010). The main passages are wider than the Rossby radius, and the lower layer reaches the surface in the central part of the straits. Actually, if the density difference is only due to salinity, the relative freshwater excess in the upper layer determines the Rossby radius (Rudels, 2010).

The transport in the boundary currents in each strait can then be estimated from Werenskiold's expression $g\Delta\rho H^2/2\rho f$, where g is the acceleration of gravity, $\Delta\rho$ the density difference between the two layers, H the depth of the upper layer at the coast, ρ the reference density, and f the Coriolis parameter (Werenskiold, 1935). If the freshwater input, F, is known, and the entrainment of Atlantic water, M_A, is estimated from the turbulent energy input at the surface, $\Delta\rho$ can be determined and the outflow $M_A + F$ of upper layer water can be computed (Stigebrandt, 1981; Rudels, 1989).

Spall (2012) adopted a different conceptual approach. He examined marginal seas and applied cooling in the central basin and a geostrophic boundary current bringing heat into the system. Eddy exchanges between the boundary current and the interior balance the heat loss and correspond to the entrainment of Atlantic water into the upper layer in the previous description. The boundary current becomes denser and exits as a deep overflow (Spall, 2012). This picture applies for the Nordic Seas, but Spall (2013) used a similar approach for the Arctic Ocean, where the interactions take place between the boundary current and a freshened upper layer.

The double estuary description implies that the entering water is transformed into both less dense and denser water. Dense water formed in the Arctic Ocean can only exit through Fram Strait, and Rudels (2012) examined the geostrophic exchanges in the strait. He assumed that the upper layer in the Arctic Ocean was created solely by sea ice melting on top of the Atlantic water. If the amount of meltwater and the temperature and salinity of the Atlantic water are known, the distribution of heat loss between the atmosphere and ice melting can be used to determine the amount of Atlantic water transformed into upper layer water when it reaches freezing temperature. This allows for an estimate of the upper layer export in the East Greenland Current. By comparing the two water columns, the East Greenland Current and the Atlantic water in the West Spitsbergen Current, the depth of the pressure reversal below which the Atlantic water enters the Arctic Ocean can then be determined (Rudels, 1989, 2012).

To quantify the deep outflow, some of the created upper layer water was assumed to flow onto the shelves and become transformed by ice formation into brine-enriched, dense water that recrosses the shelf break, sinks down the slope, and entrains Atlantic water. The denser water in the East Greenland Current water column below the upper layer then leads to another pressure reversal, below which the inflow of Atlantic water is arrested and the deep water exits the Arctic Ocean. This approach involves many assumptions about dense water formation on the shelves and entrainment at the slope that are elaborated further in Rudels (2012).

One finding is that no baroclinic balance between the inflows and outflows can be established. If only the estuarine circulation is present, the inflow below the pressure reversal can only be stopped by a sea level slope and a barotropic pressure head directed out of the Arctic Ocean. In the case of a double estuary, the deep outflow cannot be arrested and sea level decreases in the Arctic Ocean, which generates a balancing barotropic inflow in the West Spitsbergen Current. Another possibility would be a still denser water mass in the Nordic Seas that creates a further deep pressure reversal. Only if the deepest pressure reversal is close to sill depth would the baroclinic exchanges approximately balance. Mass (volume) balance in the Arctic Ocean should be established within months, but the baroclinic freshwater exchange might take years to reach a balance between input and outflow—and perhaps a balance is never achieved.

One interesting question concerns whether or not a double estuary circulation could be created in an Arctic Ocean with shelves and heat loss but with no freshwater input. Ice formation on the shelves would lead to brine rejection, dense water formation, and slope convection, thus sustaining the overturning loop. The ice would melt partially by solar radiation in summer and by heat entrained from Atlantic water below in winter, and a less dense upper layer would form, establishing the upper estuarine part of circulation. Freshwater input would then not be needed.

Double estuary circulation has been further elaborated in conceptual models by, for example, Lambert et al. (2016) and Haine (2021). These models ignore, as do most conceptual models and also the approach presented here, the inflow over the Barents Sea. The Barents Sea inflow is largely barotropic and mainly forced by wind and sea level slope and cannot easily be incorporated in the baroclinic description used for double estuary exchanges through Fram Strait.

FRESHWATER STORAGE AND UPPER LAYER CIRCULATION

The least saline upper layer is found in the Amerasian Basin, and in particular in the Beaufort Gyre, where the water column stores more than 20 m of freshwater (relative to 34.80). This accumulation of freshwater is attributed to the clockwise atmospheric circulation over the Beaufort Sea that drives Ekman transports toward the center of the gyre, creating a deep bowl of low salinity water. Such accumulation cannot go on indefinitely, and the deeper part of the bowl becomes baroclinically unstable and sheds eddies into the surrounding waters. Model studies by Manucharyan and Spall (2016) indicate that these two processes should balance when the freshwater storage in the gyre reaches around 34 m. This is, however, much more than observed, suggesting that not all processes are taken into account.

There is another mechanism that can reduce the freshwater accumulation. As the gyre is spun up by the wind, the concentration of low salinity water at the center creates a density distribution that generates a clockwise geostrophic flow, but in summer, when the winds are weaker, the atmospheric forcing of the ice almost disappears. Instead, the ice cover retards, by friction, the underlying geostrophic circulation and flattens the isopycnals. This process adds to the eddy shedding in limiting the freshwater accumulation and should keep it around the 20 m that is presently observed (Meneghello et al., 2018). However, if, in a warming climate, the ice cover decreases in thickness and compactness, its braking capability is reduced, which allows for more freshwater storage in the Beaufort Gyre (Doddridge et al., 2019).

The liquid freshwater content in the Arctic Ocean has increased from 93,000 km^3 during the last two decades of the twentieth century to 101,000 km^3 during the first decade of the twenty-first century. At the same time, the sea ice volume has decreased from 17,800 km^3 to 14,300 km^3, providing about two-thirds of the freshwater input. Almost all of this freshwater increase is concentrated in the Beaufort Gyre, from 18,500 km^3 to 23,500 km^3 (Haine et al., 2015). Superficially it appears as if the sea ice meltwater added to the upper layer has been concentrated in the Beaufort Gyre.

Proshutinsky et al. (2019) analyzed different sources that contributed to freshwater storage in the Beaufort Gyre between 2003 and 2018 and found that the largest input, 15% to 45%, came from the Mackenzie River, but it was strongly dependent on atmospheric forcing. A clockwise circulation draws the water into the gyre, while an anticlockwise circulation carries the Mackenzie runoff directly to the Canadian Arctic Archipelago. The Bering Strait inflow could contribute between 5% and 50%, again depending on the year, while melting of sea ice and downward Ekman pumping of sea ice meltwater in the center of the gyre contribute between 10% and 20% of the freshwater anomaly. Low salinity waters derived from the Eurasian shelves are also found in the Beaufort Gyre, but the input depends upon the wind field. When the clockwise circulation is weak over the Amerasian Basin and the anticlockwise circulation is strong over the Eurasian Basin, the anticlockwise gyre in the Eurasian Basin expands into the Makarov Basin, and some of its water is drawn into the Beaufort Gyre (Morison et al., 2012). The main conclusion, however, is that the present large freshwater storage in the Beaufort Gyre is due to a persistent clockwise atmospheric circulation that has forced the upper low salinity layers toward the gyre.

INTERNAL MIXING PROCESSES

Wind and the seasonal heating and cooling cycle are the main external forcings on the Arctic Ocean. In winter, the upper layer is homogenized by ice formation and brine rejection, and wind stress reaches down to the strong permanent halocline. In summer, sea ice melting creates a low salinity meltwater layer that inhibits deep wind mixing in spite of more open water and more mobile ice floes leading to stronger stirring. Some solar radiation penetrates below the meltwater layer and creates a near-surface temperature maximum that might, or might not, survive the deepening of the Polar Mixed Layer the following winter (Jackson et al., 2010).

The deep interior of the Arctic Ocean is shielded from surface forcing by its strong stability, but mixing processes using other energy sources may be important in the deeper layers. Tidal motions affect the entire water column, but when they interact with bottom topography, both well-mixed turbulent bottom layers and internal tides are generated. The Arctic Ocean is largely located north of the critical latitude (75°N) where the inertial period is shorter than the M2 tidal period. Internal tides then cannot propagate but instead dissipate their energy where they are created, especially above the continental slopes (Rippeth et al., 2015).

Another internal process is double-diffusive convection, where, if one component, heat or salt, is unstably stratified, the potential energy stored in the unstable density distribution can be released by the more rapid molecular diffusion of heat. An unstable stratification in salinity, saline water above fresh, is uncommon in the Arctic Ocean, while, as a β ocean, an unstable distribution of temperature, cold water over warm, is the norm in the upper layers above the Atlantic temperature maximum. This leads to formation of diffusive interfaces. Heat diffuses through the interfaces, generating unstable layers, warm above and cold below the interface, that eventually grow unstable and convect, homogenizing the layers above and below. This diffusive-convective process creates thermohaline staircases that are especially prominent in the deep thermocline above the Atlantic layer in the Canada Basin (Neal et al., 1969) but are also present in the other basins.

Double-diffusive convection is primarily a vertically driven process, but it can induce lateral exchanges between water masses through thermohaline intrusions, which are observed almost everywhere in the Arctic Ocean. The classical theory for intrusion formation (Stern, 1967) requires that one component is unstably stratified and that lateral, density-compensating gradients of both heat and salt are present. Small disturbances will grow when salt is unstably stratified, and the perturbations are such that warm intrusions rise and cold intrusions sink across the front. If heat is unstably stratified, rising cold and sinking warm intrusions will grow. A warm intrusion has a diffusive interface above and a salt finger interface below, while the situation is reversed for a cold intrusion. The motions are driven by the differences in density fluxes through the two interfaces. Thermohaline intrusions in the Arctic Ocean are, however, observed in almost all types of stratification, and also when both components are stably stratified and where the classical approach does not apply. They are less frequent and less developed when the background stratification is in the salt finger sense, which was the situation examined by Stern.

Thermohaline intrusions, and also individual eddies, are generated at and spreading from narrow fronts between water columns with different properties. The strongest front in the Arctic Ocean is located above the Kara Sea slope between the warm, saline Fram Strait branch and the colder, fresher Barents Sea branch (**Figure 5**). Intrusions there are observed in the diffusively unstable part above the temperature maximum, in the stable-stable range between the temperature and salinity maxima, and also below the salinity maximum, where they are most strongly developed in the stable-stable part below the intermediate salinity minimum.

When both components are stably stratified, finite lateral disturbances are needed to create initial inversions that eventually evolve into diffusive and salt finger interfaces. Such disturbances could be created by internal tides that carry waters across the front. However, intrusions are also found on the basin side of the Fram Strait branch (**Figure 5**). This raises the question of the importance of intrusions in spreading heat from the Atlantic water at the boundary to the interior of the basins. One view is that the intrusions grow laterally and reach well into the center of the basins (Walsh and Carmack, 2003). A second view assumes that the expansion of the intrusions is limited to the frontal zone. After the potential energy stored in the unstably stratified component is removed, the intrusions are advected as relicts with the main circulation (Rudels et al., 1994; Rudels and Hainbucher, 2020).

The intermediate waters on the basin side of the Fram Strait branch have characteristics that can only derive from the Barents Sea inflow branch at the Kara Sea slope. This implies that the water entering the boundary current from the Kara Sea shelf must move into the basin from the Laptev Sea slope farther east. The Barents Sea branch is located on the slope side of the Fram Strait branch, suggesting that substantial fractions of the two inflow branches as well as the intrusions created between the branches also leave the slope and move toward Fram Strait within the Nansen Basin (**Figures 4 and 5**).

There is a possible connection between thermohaline staircases and thermohaline intrusions. Transports through the interfaces are commonly taken to depend upon the magnitude of the unstable density step, $\alpha\Delta T$ or $\beta\Delta S$, raised to the 4/3 power (Turner, 1973). An intrusion created in the thermocline above the temperature maximum has an unstable temperature step $\alpha\Delta T$ at the diffusive interface that is larger than the corresponding unstable salinity step $\beta\Delta S$ at the salt finger interface. This leads to stronger density

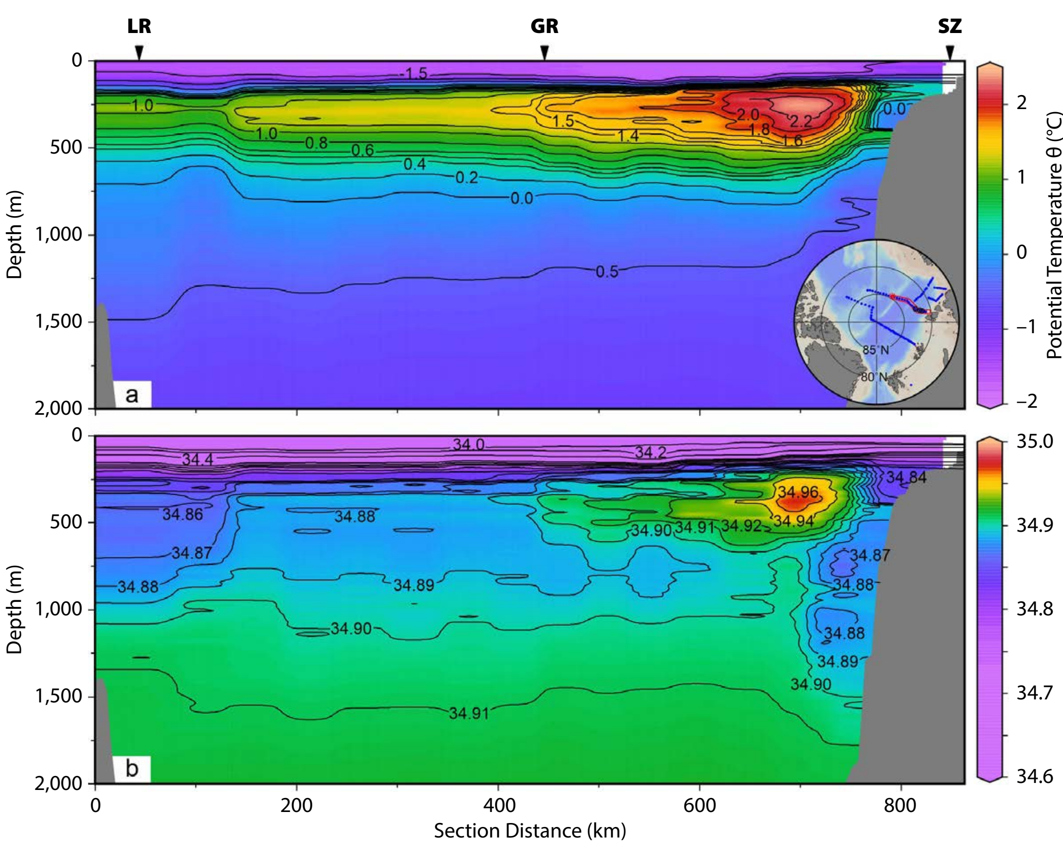


FIGURE 5. Potential temperature (a) and salinity (b) sections across the Nansen Basin from Severnaya Zemlya (SZ) over the Gakkel Ridge (GR) to the Lomonosov Ridge (LR) (the section position is indicated on the (a) inset) showing the cold, less saline Barents Sea branch entering the Nansen Basin at the continental slope and the presence of Barents Sea branch water over Gakkel Ridge and in the Amundsen Basin. Thermohaline intrusions are present between the warm, saline Fram Strait branch and the Barents Sea branch at the slope and in the interior of the Nansen Basin (observations from *Polarstern* 2011).

transport across the diffusive interface, and the stabilizing temperature step at the salt finger interface is eventually removed. The more saline upper and the less saline lower layers then merge, transforming the intrusive layers into a thermohaline staircase with thick homogeneous layers and small stability ratios (Rudels, 2021).

Such thick layers have been observed at the Laptev Sea slope and in the Eurasian Basin (Polyakov et al., 2012b, 2019). These staircases could transfer heat from the Atlantic water to the surface layer and the ice cover in the Nansen Basin. In the other basins, especially the Canada Basin, where the staircases have high stability ratios, such transfer is less likely. The fluxes there are smaller, and the thermocline lies below the temperature minimum created by the inflow of Bering Strait winter water, which prevents further vertical transfer of the heat.

The nonlinearity of the equation of state for seawater induces other effects. Cabbeling, or contraction on mixing (Witte, 1902; Foster, 1972), causes the mixture of two waters with different temperatures and salinities to become denser than the initial waters. Smith et al. (1937), suggested that cabbeling could be important in the formation of the intermediate layers in the Labrador Sea by lateral mixing between waters from the rim and from the central core. However, the nonlinearity decreases with increasing temperature, salinity, and pressure, and the contraction is less in the deeper layers. Furthermore, the density increase does not take place before the mixing is complete down to the molecular level, which requires strong turbulent stirring to rapidly reach the appropriate mixing length scale (Eckart, 1948), which likely limits its importance. Molecular mixing and diffusion rather suggest that cabbeling should be considered as a perturbation on double-diffusive convection, making the density fluxes into the colder water above less intense than those into the warmer water below the interfaces, causing the interface to move upward (McDougall, 1981a, b).

Another nonlinear feature is that cold water is more compressible than warm—the thermobaric effect. This implies that an externally forced downward displacement in a weakly stratified water column with unstable temperature but stable salinity distribution might grow and convect. In contrast to double-diffusive convection and cabbeling, the thermobaric effect does not require mixing to be triggered, and once it has passed the critical density threshold it would continue to sink (Gill, 1973). It is also asymmetric: cold water might be induced to sink, but warm water will not rise.

The thermobaric effect also affects lateral mixing between water masses (John Shepard, *pers. comm*., 1979), especially between a boundary current and the basin interior. If the isopycnals slope upward from the coast, as is the case of a warm buoyant boundary current (Atlantic inflow), the exchange trajectories between the boundary current and the interior will not be along but rather below the isopycnals, spreading the boundary current downward. In the case of a cold, less saline boundary current with isopycnals sloping upward from the coast (polar outflow), the exchanges between the boundary and the interior will take place above the isopycnals, concentrating and confining the boundary current to the surface. If the isopycnals slope downward from the boundary, as is the case for a deep, cold overflow, the exchange trajectories are again below the isopycnals and the boundary current spreads downward. Aagaard et al. (1985) noticed that the outflow of warmer Arctic Ocean deep water in the East Greenland Current was located around 2,000 m above the colder Greenland Sea deep water and attributed this to the thermobaric effect.

OUTLOOK

As noted in the introduction, Quadfasel et al.'s (1991) observations of Arctic warming three decades ago altered our perception of the Arctic Ocean, from being a place in steady state to one that is highly variable. They expressed the urgent need to understand this system under a rapidly changing climate. Indeed, today the persistent loss of sea ice has become the leading signal of global warming, and few current papers fail to mention that the Arctic is warming two to three or more times faster than the rest of the planet. Our effort in this paper has been to emphasize the structure of the Arctic Ocean and the key mechanisms that determine that structure. In our opinion, two questions are clear in looking to the coming three decades: (1) How will the structures, functions, and fluxes of the interior ocean respond to climate forcing? (2) How will biogeochemical systems respond to an Arctic Ocean in transition?

As a β ocean, there are few physical processes and biogeochemical functions that are not constrained by the regionality and seasonality of freshwater supply, disposition, storage, phase, and export to the global ocean (Carmack et al., 2016). In the coming years, the hydrological cycle of poleward freshwater transport is expected to increase, and this would result in stronger stratification and reduced vertical fluxes of heat and material properties. System-wide complex interactions, however, make predictions difficult. In terms of supply, for example, quantification of river inputs will require better estimates of trans-evaporation, lake effects, and permafrost thaw within surrounding drainage basins. The freshwater phase (i.e., solid, liquid, or vapor) will depend on the global rate of climate warming and interactive air-ice-sea heat exchanges. The future of freshwater disposition, storage, and export will respond to new patterns of wind forcing and coupling as the ice cover progressively retreats in summer. Responses will definitely be spatially heterogeneous, as for example are the opposite responses of the Eurasian and Amerasian Basins to climate forcing thus far (Polyakov, 2020). Seasonal signals are strengthened; the area of seasonal melting and freezing is already growing, currently increasing the seasonal burden of freshwater in the summer mixed layer. Later, however, the seasonal melt rate might decrease as the Arctic Ocean grows more ice-free year-round (Brown et al., 2020). In the long run, the control of export relative to storage, the systemwide freshwater residence time, will determine whether the Arctic will freshen or not, and much remains uncertain.

Other scenarios exist. While a warmer climate could increase the freshwater input and strengthen the upper loop, a warmer Atlantic water might lead to a larger fraction of oceanic heat going to ice melting, increasing the stability between the upper and the Atlantic layer, reducing entrainment from below, and weakening the upper estuarine circulation. This reduction might be stronger than the increase due to larger runoff. At the same time, the salinity on the shelves becomes lower and the production of saline shelf water diminishes, leading to a weakening of the overturning loop. A warmer climate would then result in an overall weaker double-estuary circulation.

One part of the double-estuary circulation that has already diminished is the deep and bottom water formation in the Greenland Sea. The deepest layers are no longer renewed by local convection, but by advection of deep waters from the Eurasian and Amerasian Basins. The water now formed in the Greenland Sea is Arctic intermediate water, less dense than the Amerasian Basin deep water. Hence, the thermohaline roles of the Greenland Sea and the Arctic Ocean have changed (Marnela et al., 2016). The Greenland Sea no longer forms the densest water in the Arctic Ocean-Greenland Sea system, but it might now provide the densest component of the overflow water to the North Atlantic.

Biogeochemical systems will respond in multiple ways to a changing physical environment, but three questions are germane: (1) Will new production increase or decrease? (2) Will acidification threaten marine organisms? (3) Will northward spreading waters and organisms from subarctic seas displace existing ecosystems? With regard to the first, the Arctic Ocean is decidedly an oligotrophic system. The balance is between increasing light input owing to sea ice retreat and decreasing nutrient supply owing to increased salt and heat stratification. The two mechanisms also interact, as ice retreat beyond the shelf break will increase upwelling of nutrient-rich waters, while increased nutrient supply may result in self-shading and reduced light availability. Acidification is typically reported in terms of aragonite undersaturation (omega) values, and the central Canada Basin was the first deep ocean region in which omega fell below its critical value, making the waters corrosive (Yamamoto et al., 2009). Introduction of new species by advection from subarctic waters or invasion due to changing environmental conditions will impact the food web through complex, cascading mechanisms.

Quadfasel et al.'s observations were a wake-up call. But, as recalled by Aagaard and Carmack (1989), the message of change was preached almost a century earlier by Fridtjof Nansen himself: he ended a lecture on the *Fram* drift, delivered in 1897, with these words: "Everything is drifting, the whole ocean moves ceaselessly, a link in Nature's never-ending cycle, just as shifting and transitory as the human theories." Would Nansen judge us ready for the future?

FURTHER READING

The presentation of the processes and circulation of the Arctic Ocean given here represents our personal views and reflections. It is drawn with broad brushes, and the number of references is kept low. Other recent summaries of the Arctic Ocean circulation that include many relevant references and discussions are Bluhm et al. (2015, 2020), Rudels (2019, 2021), Wassmann et al. (2020), Timmermans and Marshall (2020), and Lenn et al. (2021).

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TURBULENT MIXING
IN A CHANGING ARCTIC OCEAN

By Tom P. Rippeth and Elizabeth C. Fine

The ice edge in the Nansen Basin 650 km from the North Pole in August 2013. *Photo credit: Tom Rippeth*

ABSTRACT. Historically, the Arctic Ocean has been considered an ocean of low variability and weak turbulent mixing. However, the decline in seasonal sea ice cover over the past couple of decades has led to increased coupling between the atmosphere and the ocean, with potential enhancement of turbulent mixing. Here, we review studies identifying energy sources and pathways that lead to turbulent mixing in an increasingly ice-free Arctic Ocean. We find that the evolution of wind-generated, near-inertial oscillations is highly sensitive to the seasonal sea ice cycle, but the response varies greatly between the continental shelves and the abyssal ocean and between the eastern and western ocean basins. There is growing interest in the role of tides and continental shelf waves in driving mixing over sloping topography. Both dissipate through the development of unsteady lee waves. The role eddies play in transporting shelf water into the basins and in supporting mixing has become more apparent as technological advances have permitted higher resolution observations of sea ice retreat. The importance of the dissipation of unsteady lee waves and of eddies in driving mixing highlights the need for parameterizations of these phenomena in regional ocean models and climate simulations.

INTRODUCTION

The Arctic Ocean plays a key role in regulating global climate. The high albedo of sea ice, which covers most of the Arctic Ocean, acts to cool the Northern Hemisphere. Waters of Atlantic and Pacific origin are transformed through cooling and freshening as they pass through the Arctic Ocean system. Over the past couple of decades, the Arctic has been warming at a greater pace than the global mean, with the clearest regional consequences being a rapid decline in sea ice extent and thickness.

Although the Arctic Ocean only accounts for about 1% of the global ocean by volume, it receives approximately 10% of global river discharge (Haine et al., 2015). Coupled with an excess of precipitation over evaporation and the seasonal ice freeze-melt cycle, this discharge results in an ocean that is predominantly salinity stratified—a layer of fresher water overlies saltier water, with a halocline between the two layers. The halocline plays a key role in isolating the main oceanic heat source, intermediate-depth Atlantic Water, from the sea surface and consequently sea ice. The fluxing of this intermediate-depth heat toward the surface, and hence its role in melting sea ice, is mediated by vertical exchange processes.

Across much of the global ocean, vertical exchange is dominated by turbulent stirring of gradients, which enhances mixing rates to many orders of magnitude above that of molecular diffusivity. Globally, the two main sources of mechanical energy supporting turbulent mixing are winds and tides, with the generation of internal waves providing a key energy pathway from forcing scales to the turbulent dissipation that supports mixing. The energy levels associated with the internal wave field are weak in the Arctic Ocean, several orders of magnitude below that typically observed at lower latitudes (Levine et al., 1987; Pinkel, 2005).

The weak internal wave field has been attributed to several factors unique to the Arctic Ocean. The direct wind forcing of the ocean is weakened on account of the decoupling of the ocean from the atmosphere by sea ice (Morison et al., 1985; Pinkel, 2005). Also, the high latitude of the Arctic Ocean prevents the generation of freely propagating linear internal tides (Vlasenko et al., 2003), a major source of turbulent mixing at lower latitudes. Furthermore, internal waves are frictionally damped on the underside of sea ice (e.g., Janout and Lenn, 2014; Carr et al., 2019).

A consequence of the Arctic Ocean's weak turbulent mixing, combined with the opposing vertical heat and salt gradients across the halocline, is the formation of double diffusive staircases capping the intruding Atlantic Water across much of the interior of the Arctic Ocean (Padman and Dillion, 1987, 1988; Timmermans et al., 2008a; Fer, 2009; Guthrie et al., 2013; Sirevaag and Fer, 2012; Shibley et al., 2017). These staircases support weak vertical heat fluxes (0.02–0.30 Wm^{-2}) that, Arctic-wide, are estimated to account for about 10% of the total heat flux to the sea ice, with seasonal solar heating dominating (Timmermans and Marshall, 2020).

Staircases support higher heat fluxes over the continental slope of the eastern Eurasian basin (~1 Wm^{-2}; Polyakov et al., 2019). However, because they are not sufficient to explain the observed cooling and freshening of the intermediate-depth Atlantic Water along the shelf break, the presence of enhanced mixing processes that are episodic in space and time is likely (Lenn et al., 2009; Schulz et al., 2021b). A staircase cannot be sustained above a critical level of intermittent turbulence (Shibley and Timmermans, 2019), suggesting that the absence of staircases over continental slope regions in the western Eurasian Basin indicates significant turbulent mixing. Over the continental slope around the Yermak Plateau, vertical turbulent heat fluxes of up to 100 Wm^{-2} have been estimated (Padman and Dillon, 1991; D'Asaro and Morison, 1992; Meyer et al., 2017; Fer et al., 2020).

Here, we review recent studies of Arctic Ocean mixing processes, identifying key forcing mechanisms and energy pathways, and examine the changing impact of wind and stratification on turbulent mixing in an increasingly ice-free Arctic Ocean.

WIND-DRIVEN INERTIAL OSCILLATIONS

Over recent decades, declining seasonal sea ice extent and the consequent increasing exposure of open water to surface wind stress have resulted in increased transfer of momentum from the atmosphere to the ocean on both basin (e.g., Giles et al., 2012; Armitage et al., 2017) and local scales (e.g., Rainville et al., 2011; Martini et al., 2014; Dosser and Rainville, 2016). Moreover, there is growing evidence of changes in wind-ice-ocean coupling in response to the changing nature of the sea ice associated with the widespread loss of thick, multiyear ice floes (Martin et al., 2014; Cole et al., 2017).

Observations from the shallow Chukchi and Laptev continental shelf seas reveal a pronounced seasonal signal in inertial currents and associated shear that is strongly correlated with the annual cycle of sea ice concentration and the passage of storms during open water periods (Rainville and Woodgate, 2009; Lenn et al., 2011). In both cases, the inertial currents were observed to penetrate the full water column (depth ~100 m), with an increasing phase lag with depth leading to enhanced shear, consistent with the structure of inertial currents observed in stratified temperate shelf seas (e.g., the North Sea; Knight et al., 2002).

A microstructure time series in the Laptev Sea indicates significant intermittency in midwater dissipation, with a three orders of magnitude increase following the alignment of the shear vector with the surface stress vector imposed by the movement of the sea ice (Lenn et al., 2011). These are consistent with a surface stress-shear alignment mechanism proposed for damping of inertial oscillations, and associated mixing, in temperate stratified shelf seas (Burchard and Rippeth, 2009).

While the ice-free shelf sea response to wind-driven inertial oscillations mirrors that at lower latitudes, within the central basins the depth penetration of the energy associated with inertial oscillations is limited on account of the high latitude position of the Arctic Ocean. At these latitudes, the gradient of planetary vorticity (β) is low, limiting depth penetration of the inertial shear (D'Asaro et al., 1995). A recent modeling study shows the combination of low β and shallow mixed layers can result in a sixfold reduction in near-inertial band energy in the Arctic Ocean as compared to similar mid-latitude scenarios (Guthrie and Morison, 2021). The inertial band energy is likely further reduced by the shoaling of the surface mixed layer (e.g., Timmermans et al., 2012).

Peralta-Ferriz and Woodgate (2015) show an almost ubiquitous shoaling of the surface mixed layer, of order 0.5–1 m yr^{-1}, over the past three decades across all the major Arctic basins and in all seasons. The shoaling trends coincide with surface mixed layer freshening and increased stratification. The stratification is found to dominate over the wind in determining the surface mixed layer depth during ice-free periods (Peralta-Ferriz and Woodgate, 2015). There are also significant regional differences, with similar wind speeds two to three times more effective at deepening the surface mixed layer in the eastern Arctic Ocean than the more strongly stratified western Arctic (Peralta-Ferriz and Woodgate, 2015).

Polyakov et al. (2020a) report current measurements spanning 2004–2018 from the Nansen/Amundsen Basin Observation System (NABOS) mooring array in the eastern Arctic that show increasing inertial band current speeds and associated vertical shear in the upper water column, consistent with increasing coupling between the wind and upper ocean as sea ice declines. The strengthening shear coincides with weakening upper ocean stratification, indicating an increasing potential for shear instability and associated turbulent mixing. Over the same period, vertical heat fluxes are estimated to have almost trebled, overtaking the atmospheric heating contribution in the region (Polyakov et al., 2020b).

In contrast, a microstructure survey in the western Arctic during the 2012 Beaufort Gyre Exploration Program cruise, in open water and spanning the extraordinary Arctic cyclone of August 2012 (the strongest summer storm on record; Simmonds and Rudeva, 2012), found no evidence of enhanced mixing at depth, with the thermohaline staircases preserved throughout (Lincoln et al., 2016). They report mixing rates similar to those observed under sea ice (Padman and Dillon, 1987) and in more quiescent open water conditions (Fine et al., 2021). Dosser et al. (2021) reveal a strengthening seasonal cycle in dissipation in the Canada Basin between 2004–2010 and 2011–2019, with an estimated doubling in summer. While this implies increasing heat fluxes, they are still too low to melt meaningful quantities of sea ice. They also find a decrease in winter dissipation that they attribute to reduced wind-ice-ocean drag in response to the loss of thick, multiyear ice floes.

TIDES

Stratified tidal flow over sloping topography results in the conversion of energy into an internal tide, a key energy pathway from tides to turbulent mixing. The downslope stratified flow results in the depression of the pycnocline, which, as the tide slackens, propagates away as a linear internal wave of tidal period. However, much of the Arctic Ocean is located poleward of the critical latitude at which the local inertial period matches the dominant (M2) tidal period, and so the resulting lee wave becomes bottom trapped. A consequence is a significant reduction in the efficiency of tidal conversion at these high latitudes (Vlasenko et al., 2003).

A major hotspot for enhanced midwater dissipation has been identified over the continental slope north of Svalbard and the Yermack Plateau (Padman and Dillion, 1991; D'Asaro and Morison, 1992; Fer et al., 2015; Koenig et al., 2021) that is associated with the cross-slope flowing tide (Fer et al., 2020). Here, midwater dissipations are found to be enhanced by a factor of 100, resulting in turbulent heat fluxes toward the surface of $O(10 \text{ Wm}^{-2})$. Similarly enhanced heat fluxes have been reported over sloping topography in the Beaufort Sea and extending into the Chukchi Sea (W.J. Shaw et al., 2009).

Pan-Arctic microstructure measurements show hotspots of enhanced midwater dissipation over the continental slope that correlate spatially to areas of significant tidal conversion (**Figure 1**), implicating the tide as a significant source

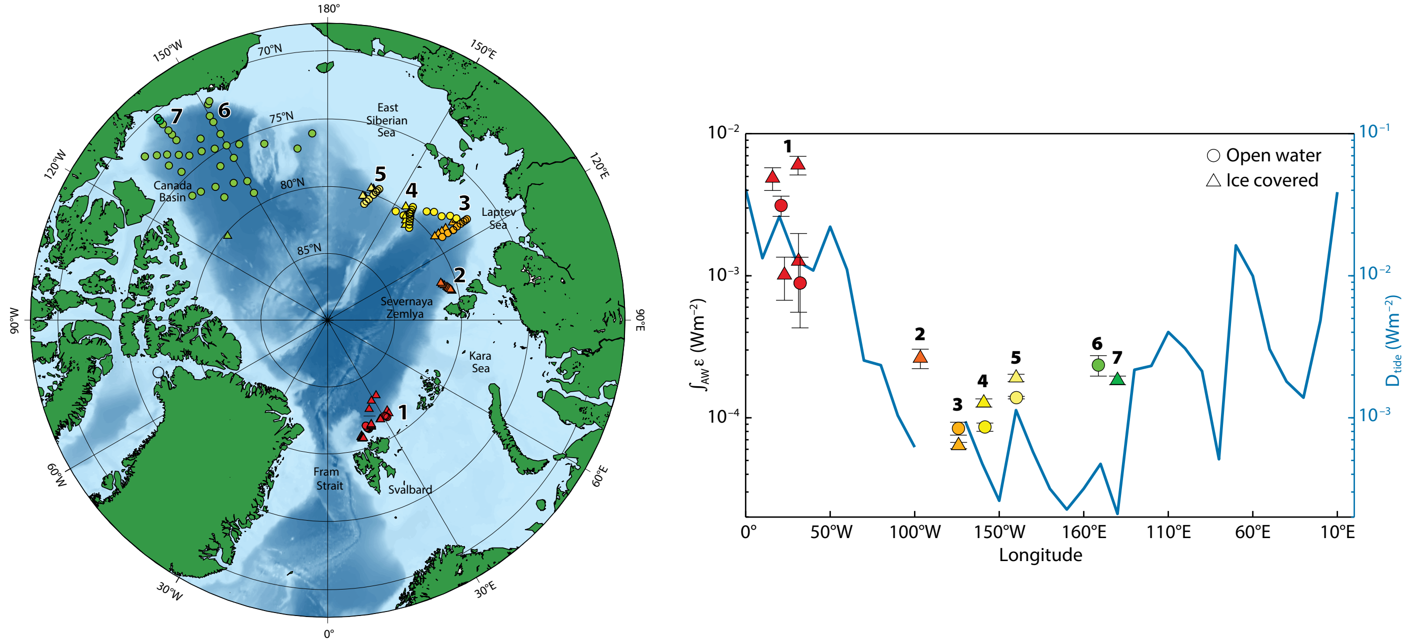

FIGURE 1. The circumpolar rate of tidal energy dissipation (D) over the continental shelf break around the Arctic Ocean. The solid line is the estimated rate of conversion of tidal energy to turbulence using altimeter data, and the symbols represent transect average midwater dissipation measurements ($\int_{AW}\varepsilon$) based on microstructure surveys. The circles indicate measurements made in open water conditions while the triangles indicate measurements under significant local ice cover. The Arctic map shows the positions of the transects. *Redrawn from Rippeth et al. (2015)*

of energy supporting enhanced midwater dissipation (Rippeth et al., 2015). Fer et al. (2020) estimate that, Arctic wide, the contribution of the tides to the diapycnal heat flux is comparable to that of double diffusion, despite their limited geographical extent.

Due to the critical latitude constraints, the energy pathway from tides to turbulence poleward of the critical latitude is nonlinear and results from the formation of an unsteady lee wave of length scale comparable to the bottom topography (Rippeth et al., 2017). A consequence of relatively slow internal wave phase speeds is that the downslope flow can become supercritical, introducing a direct nonlinear energy pathway from the tide to turbulence (Rippeth et al., 2017; Hughes and Klymak, 2019; Fer et al., 2020). Toward the end of the downslope flow, the lee wave disintegrates into a packet of freely propagating nonlinear internal waves (Rippeth et al., 2017; Figure 2). Synthetic aperture radar imagery reveals widespread nonlinear internal waves over continental shelf and slope regions in the eastern Arctic (Koslov et al., 2017; Koslov and Zubkova, 2019; Rippeth et al., 2019; Marchenko et al., 2021) that have potential to dissipate to turbulent mixing further afield.

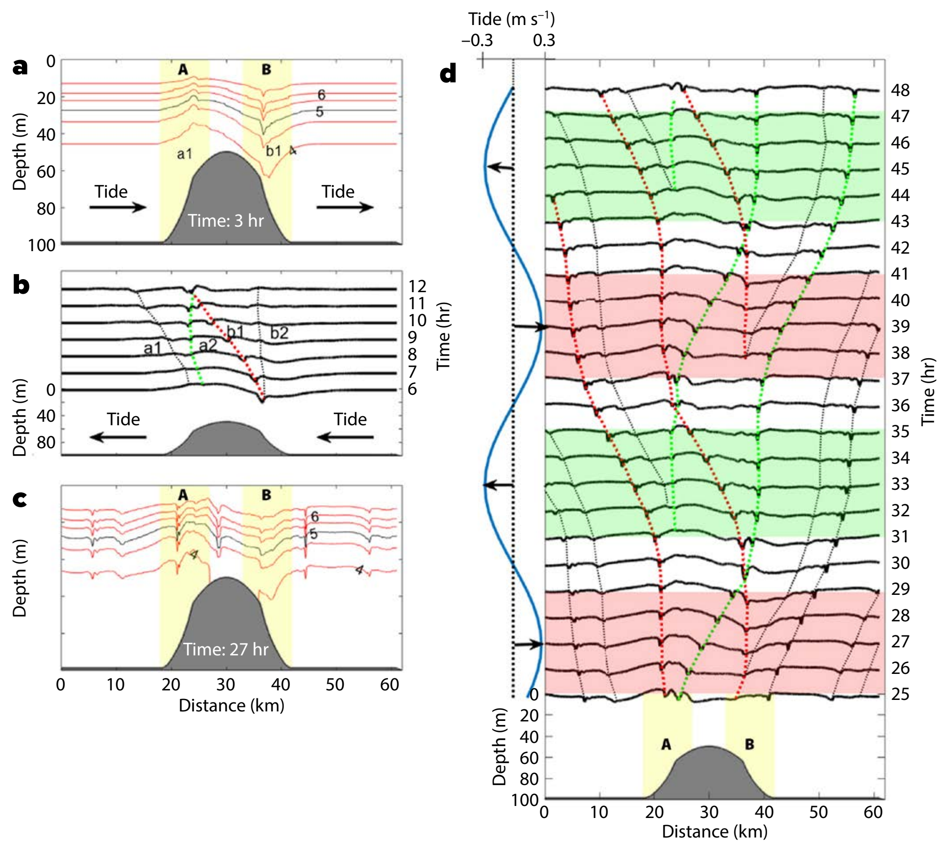

FIGURE 2. Simulated cross-bank M2 tidal flow and evolution of stratification over Spitsbergen Bank (poleward of the critical latitude for the M2 tide) constructed using a non-hydrostatic high-resolution version of the MIT general circulation model. The plots show the predicted temperature fields (4°–6.5°C isotherms at 0.5°C intervals) after (a) 3 hr and (c) 27 hr of model time. They illustrate the development of a lee wave downstream of the flow and its breakup into high frequency internal waves. The evolution of the 5° isotherm is shown in the Hovmöller diagrams: (b) t = 6–12 hr and (d) t = 25–48 hr periods of simulation with a contour interval of 1 hr. The green and red dotted lines identify the internal waves radiating away from the topography. The direction and strength of the tidal flow is shown as a solid blue line. The generation zones A and B are shaded yellow in panels (a), (c), and (d). The red and green regions in (d) indicate periods of time when the flow associated with the development of the lee wave is supercritical (Fr > 1). *Reproduced from Rippeth et al. (2017)*

REMOTELY FORCED WIND MIXING

Schulz et al. (2021a) observe significantly enhanced midwater dissipation over the continental slope poleward of the Laptev Sea, an area with weak tides (Fer et al., 2020) and low tidal conversion (Rippeth et al., 2015). Microstructure profiles reveal levels of dissipation several orders of magnitude above background that coincide with a downslope flow (maximum depth-averaged velocities ~0.5 ms^{-1}) and depression in the isopycnals, both of which are consistent with the passage of a continental shelf wave (CSW; Danielson et al., 2020). Schulz et al. (2021a) propose that the downslope barotropic flow associated with a CSW results in the development of an unsteady lee wave, implying an energy pathway to midwater dissipation similar to that of the tide.

Although some coastal sea level anomalies are a local response to propagating storms, others propagate eastward in the Arctic as CSWs of period 2–6 days. In the eastern Arctic, they tend to be generated in the Fram Strait/Barents Sea and propagate through the Kara Sea and then the Laptev Sea about one day later (Danielson et al., 2020). Danielson et al. (2020) estimate an average of 12 CSWs per year, while Shultz et al. (2021a) show that CSWs in the Laptev Sea are almost exclusively found during periods of reduced sea ice extent, pointing to enhanced far-field induced mixing during periods of reduced sea ice, particularly in the eastern Arctic.

EDDIES, SUBMESOSCALE DYNAMICS, AND LATERAL PROCESSES

Eddies are ubiquitous in the global ocean. They not only transport water properties but also act to stir water along isopycnals as they propagate, eroding large-scale gradients and contributing to diapycnal mixing. Eddies are frequently observed in the Arctic Ocean (Hunkins, 1974; Newton et al., 1974; among many others) and are typically intensified in the halocline. In many cases, eddies transport water originating in the Arctic shelf seas to the basin interior and so represent an important mechanism for ventilating the Arctic halocline (Muench et al., 2000; Spall et al., 2008).

The halocline intensification of eddies means the largest eddy velocities are frequently subsurface, which, combined with relatively small diameters (due to the high latitude), makes satellite detection difficult. Manley and Hunkins (1985) estimated that up to one-fourth of the Beaufort Sea (by area) may be filled with eddies based on profiles collected from drifting ice camps in 1975–1976. More recently, observations collected from Ice-Tethered Profilers (ITPs), hydrographic cruises, and moorings have identified hundreds of eddies (Zhao et al., 2014; Zhao and Timmermans, 2015; Zhao et al., 2018). They are predominantly anticyclonic and are mostly cold and fresh relative to the surrounding water. Kozlov et al. (2019) identified thousands of eddies from synthetic aperture radar data of which 65%–70% were cyclonic, in contrast to the preponderance of anticyclonic eddies reported from subsurface measurements. In the Eurasian basin, mooring-based studies show a nearly even split between cyclones and anticyclones (Pnyushkov et al., 2018).

Multiple formation mechanisms have been proposed to explain the origins of Arctic eddies, which are observed more frequently in regions close to topographic boundaries (Zhao et al., 2014; Zhao and Timmermans, 2015; Kozlov et al., 2019). An early proposal suggested formation due to frontal or baroclinic instability (Hunkins, 1974). Spall (1995) described a theory of eddy formation based on frontal instability that leads to subduction and generates eddies along fronts, which is consistent with observations from the northern edge of the Beaufort Gyre (Timmermans et al., 2008b; Manucharyan and Timmermans, 2013), meltwater fronts surrounding the marginal ice zone (Lu et al., 2015; Manucharyan et al., 2017), and ice edge jets (Heorton et al., 2014; Bulczak et al., 2015). More recently, MacKinnon et al. (2021) observed the subduction of an offshore jet of warm water originating from Barrow Canyon and the formation of eddies that appear to conserve potential vorticity during the subduction process (Figure 3). While (usually cyclonic) surface eddies can also form due to frontal and baroclinic instabilities, friction at the ice-ocean boundary provides a mechanism that decays the surface eddy velocity more rapidly than the subsurface signature, leaving a field of mostly intra-halocline eddies (Ou and Gordon, 1986; Meneghello et al., 2021). This observation may explain the apparent discrepancy between the satellite observations of Kozlov et al. (2019), which show a preponderance of cyclonic eddies in surface measurements in ice-free waters and the marginal ice zone, and observations of the dominance of anticyclones in subsurface measurements in the central basins (e.g., Zhao et al., 2014).

Boundary currents may also generate eddies on their flanks through baroclinic instability, as frequently observed on the Beaufort shelfbreak jet (Pickart, 2004; Pickart et al., 2005; Spall et al., 2008), and can result in the cooling of the current, as observed in the Chukchi slope current (Boury et al., 2020). Direct interactions of flows with topography may also generate eddies (D'Asaro, 1988; Cenedese and Whitehead, 2000; Chao and Shaw, 2003; P.T. Shaw and Chao, 2003; Pickart et al., 2005).

Eddies play a key dynamical role in sustaining the Beaufort Gyre. Surface Ekman convergence results in buildup of freshwater in the gyre's center. As isopycnals steepen, they become increasingly susceptible to baroclinic instability, which results in the release of relatively cold, fresh eddies from the gyre. To maintain steady state, the rate of eddy generation must balance the net transport of surface Ekman convergence over the western Arctic (Manucharyan and Spall, 2016). Furthermore, eddies' role in balancing the gyre is affected by a feedback mechanism between gyre speed and stress at the ice-

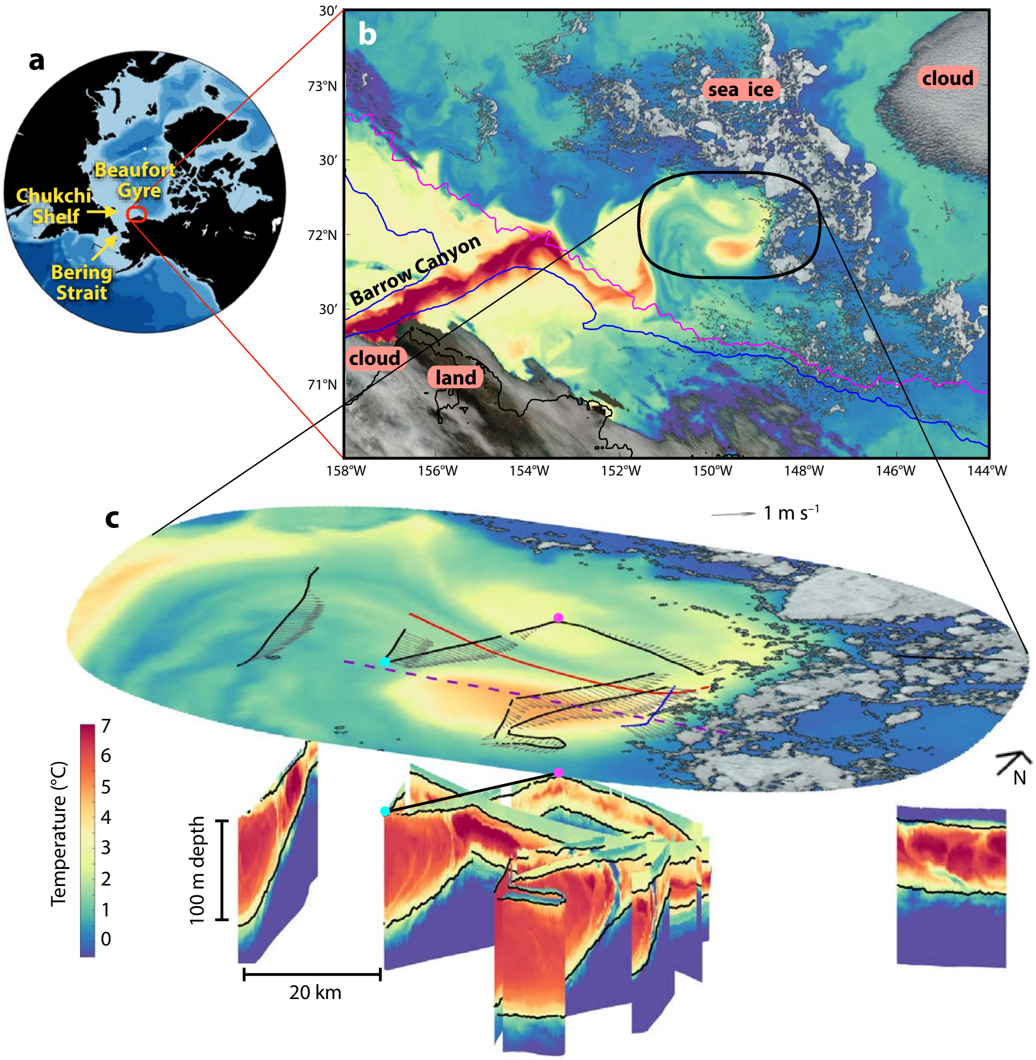

FIGURE 3. Novel high-resolution observations of the subduction and initial evolution of warm Pacific-origin water in the southern Beaufort Gyre, emphasizing the scale of these phenomena. (a) In a map of the western Arctic, the red square indicates the locations of panels (b) and (c). (b) The surface temperature signal from a hybrid MODIS satellite image collected on September 15, 2018, shows sea ice and clouds in true color and sea surface temperature (SST) in open water. The black line traces the Alaskan coast at lower left, and the 100 m and 1,000 m isobaths are shown in blue and magenta, respectively. (c) An expanded view of SST is imaged along with subsurface temperature measurements taken September 14–17, 2018, emphasizing the halocline intensification of the eddy. Observed ocean current vectors averaged over the upper 90 m are shown. The dashed purple line tracks the second FastCTD survey nine days later (shown to the bottom right). The solid black lines on the temperature contour plots indicate the 23.2 kg m^{-3} and 25.2kg m^{-3} potential density surfaces. *Redrawn from MacKinnon et al. (2021)*

ocean interface, which results in a balance between Ekman transport, eddy fluxes, and ice-ocean stress (Meneghello et al., 2018; Doddridge et al., 2019). Satellite-derived estimates of geostrophic currents under sea ice indicate that the eddy field has become an increasingly important contributor to this balance as sea ice decline has reduced ice-ocean stress in recent years (Armitage et al., 2020).

Eddies can intensify vertical mixing by locally focusing both the internal wave field and double diffusive convection. Anticyclonic eddies have low potential vorticity signatures, so that the effective Coriolis frequency within an anticyclonic eddy is subinertial. Consequently, the internal waves cannot propagate out of these eddies and instead encounter critical layers where they dissipate (Kunze, 1985). Arctic eddies have been observed to interact with the internal wave field (Halle and Pinkel, 2003; Cole et al., 2017), and Kawaguchi et al. (2014, 2016) attribute this to elevated midwater dissipation.

The hydrographic structure of warm eddies can also result in double diffusive processes that elevate turbulence and generate heat and salt fluxes from the eddy. This has been observed in both deeper Atlantic Water eddies (Dmitrenko et al., 2008; Bebieva and Timmermans, 2015) and in shallower Pacific Summer Water eddies (Kawaguchi et al., 2012; Fine et al., 2018). Double diffusion acts to transport heat upward from the tops of warm eddies and downward from their bases. Bebieva and Timmermans (2015) estimated an upward heat flux of 0.15 Wm^{-2} due to diffusive convection and a downward heat flux of 0.8 Wm^{-2} due to salt fingering. Pacific Summer Water eddies are substantially warmer, and Fine et al. (2018) used microstructure measurements to estimate an upward heat flux of 5 Wm^{-2} from an eddy on the Chukchi slope and a downward flux of 0.5 Wm^{-2}. Furthermore, the double diffusive heat fluxes associated with warm eddies may intensify as source waters warm.

DISCUSSION

A longstanding paradigm regarding the changing Arctic Ocean is that turbulent mixing will increase as a result of increased atmosphere-ocean coupling as sea ice declines (Figure 4). However, studies over the past decade have highlighted contrasting impacts of increased atmospheric coupling across different regions. Over the continental shelves, the open water response matches that at lower latitudes, resulting in a strengthening

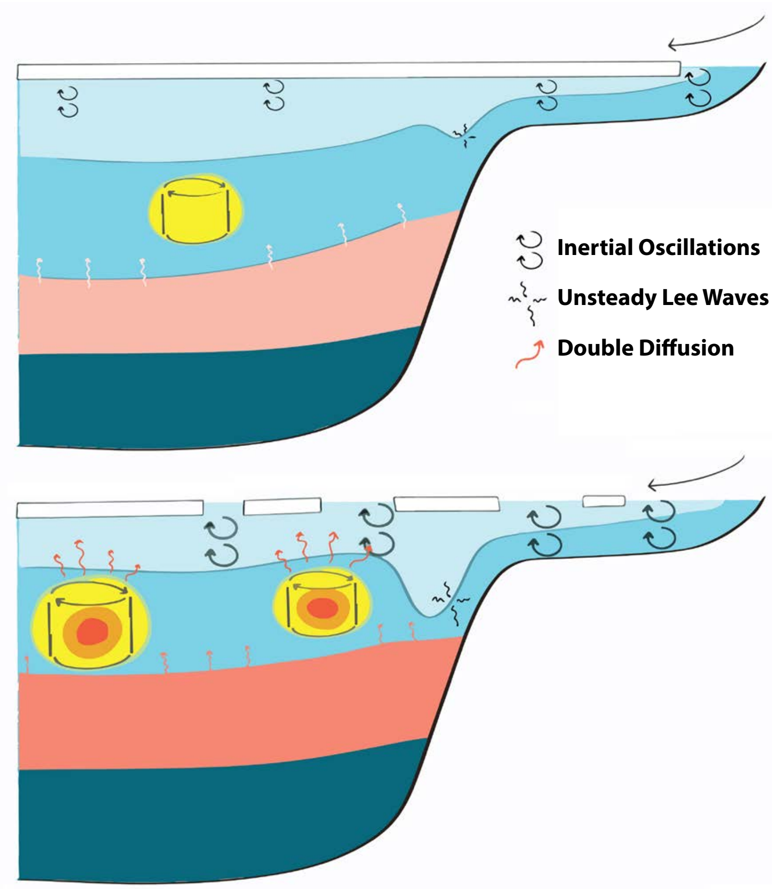

FIGURE 4. Schematic outlining the changes in turbulent mixing in a changing Arctic Ocean. Increasing ocean-atmosphere coupling combined with changes in stratification are altering the continental shelf mixing regimes, with some evidence of changing mixing patterns in the eastern Arctic Basin. Eddies are recognized as playing an increasing role in both the transport of shelf water and mixing, while the tide and far-field storms are implicated in driving mixing over the continental shelf break via the unsteady lee wave mechanism.

seasonal mixing cycle in response to declining seasonal sea ice extent, which in turn impacts atmospheric heat uptake, the duration of seasonally ice-free periods, and the properties of shelf waters exported to basin interiors.

In the ocean basins, shoaling surface mixed layers and high latitude conspire to limit the depth penetration of near-inertial energy (Guthrie and Morison, 2021). The shoaling of the surface mixed layer is predominantly a result of stratification changes and is linked to the large-scale dynamics through changes in freshwater budgets (Peralta-Ferriz and Woodgate, 2015). There is also strong evidence of differing responses across the eastern and western basins.

In the eastern Eurasian basin, a new positive feedback mechanism is identified in which reduced sea ice extent promotes more energetic inertial currents, leading to increased ventilation of the Atlantic Water and increased sea ice melt (Polyakov et al., 2020a). The enhanced mixing is a consequence of increasing inertial band currents combined with weakening upper ocean stratification (Polyakov et al., 2020b). Over the past decade, the changing stratification in this region is partly explained by changes further afield, including the warming and increasing salt content of the inflowing Atlantic Water (Polyakov et al., 2017, 2020b; Barton et al., 2018).

In contrast, in the western Arctic, the intermediate-depth oceanic heat reservoirs remain relatively isolated from the surface mixed layer by halocline stratification, ensuring negligible ice-Atlantic Water heat feedback (Lincoln et al., 2016; Dosser et al., 2021; Fine et al., 2021). However, heat that has been accumulating in the halocline for the past three decades is linked to a fivefold increase in summer heat absorption associated with reduced sea ice coverage in the northern Chukchi Sea (Timmermans et al., 2018), emphasizing the potential for the changing shelf mixing environment to impact sea ice coverage in the central basins.

Although much of the Arctic lies poleward of the critical latitude where freely propagating linear internal tides cannot be generated, the role of tides in driving turbulent mixing in the Arctic Ocean has been increasingly recognized. While the geographical influence of tidal mixing is largely limited to the shelf and shelf break (Rippeth et al., 2015; Fer et al., 2020), the latter forms an important pathway for the intruding warm Atlantic and Pacific waters. The main mechanism identified for the conversion of tidal energy to midwater turbulence is the formation of unsteady lee waves, with the development of near-critical and supercritical flow dominating tidal conversion (Rippeth et al., 2017). Both processes are stratification dependent. In particular, the weakening of upper ocean stratification could lengthen periods of enhanced mixing (Fer et al., 2020) and thus increase the rate of tidal conversion, with potential for extension to regions of weaker tides.

Tides can also interact with other mechanisms to enhance midwater mixing. These could include continental shelf waves (Schulz et al. 2021a) and variations in background flow (e.g., Aksenov et al., 2011). Accordingly, temporal and spatial changes in any of these phenomena, for example, linked to changing storminess, stratification, or sea ice decline, will impact future geographic extent of associated midwater mixing over sloping topography. While unsteady lee waves provide a major source of midwater mixing, they have relatively short length scales and so are not resolved in current state-of-the-art regional ocean models or climate simulations, emphasizing the need for their parameterization.

Eddies are also shown to make an

important contribution to setting water column properties. Armitage et al. (2020) and Doddridge et al. (2019) suggest that as sea ice drag has decreased due to sea ice decline, eddy kinetic energy has increased, as increased Ekman convergence leads to steepening isopycnals, which are then susceptible to baroclinic instability. An increase in lateral stirring by eddies could substantially impact stratification, particularly where vertical mixing is weak. Observations by MacKinnon et al. (2021; Figure 3) emphasize the small horizontal scales associated with eddies, which are not resolved by regional forecast models or climate simulations, underscoring the need for the development of new eddy mixing parameterizations to improve the predictive skill of these models.

Although this review focuses on the role of turbulence in stirring up intermediate-depth heat, inflowing Atlantic and Pacific waters are also the main supply of nutrients to the Arctic Ocean (Torres-Valdes et al., 2013). Consequently, the changing mixing patterns, coupled with changes in stratification, may directly impact primary productivity. As seasonal sea ice has declined, net primary productivity has increased by at least 30%, with a particularly strong response in the eastern Arctic Ocean where a 110% increase in primary productivity is reported over the Laptev Sea shelf break region (Arrigo and van Dijken, 2015). This is a region of recent increasing near-inertial currents and declining upper ocean stratification (Polyakov et al., 2020a,b) and where midwater depth mixing events are intermittent (Shultz et al., 2022). The impact of changing mixing patterns and stratification on limiting nutrient fluxes together with knock-on effects on primary production, the food web, and carbon sequestration is an important area of ongoing work.

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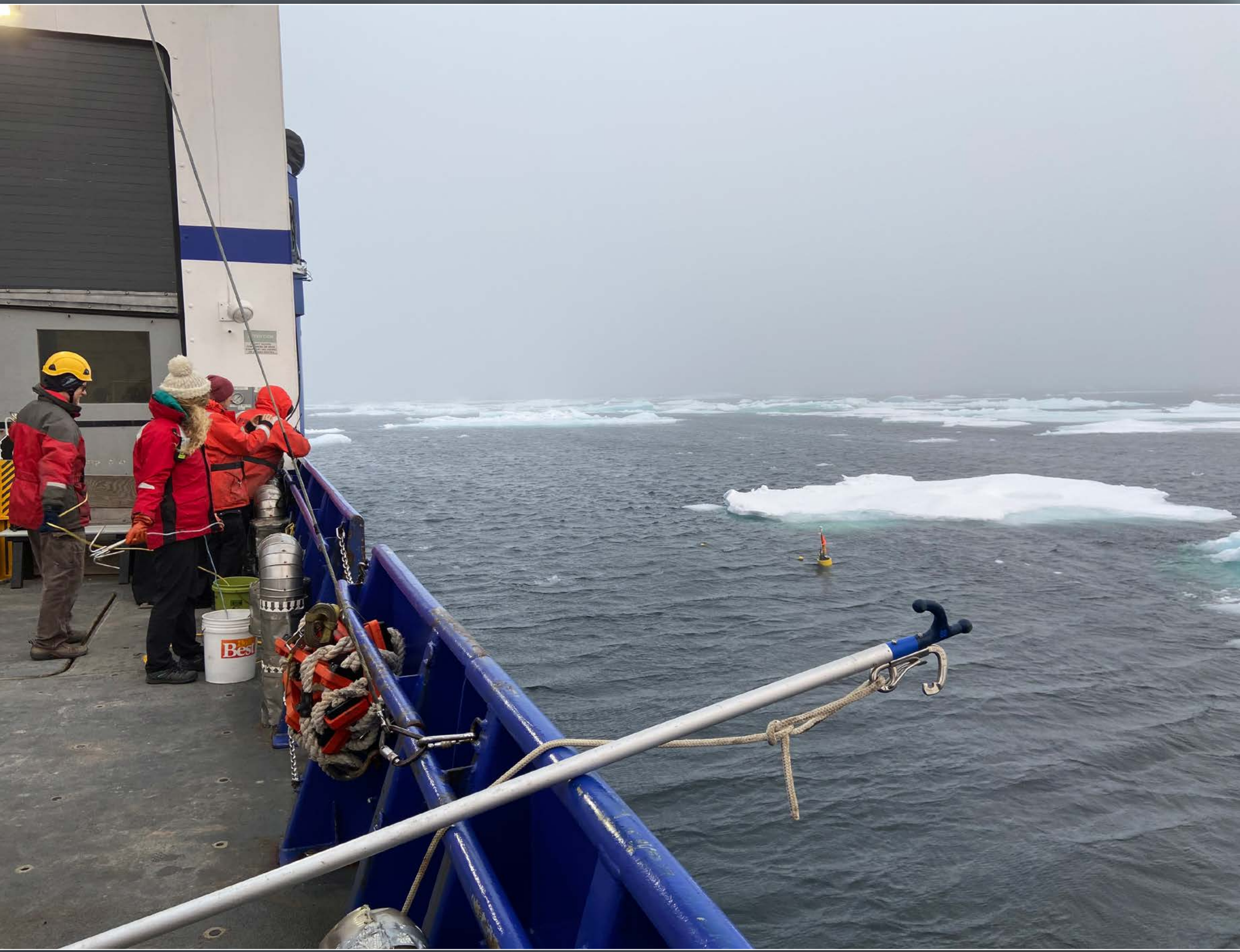
AIR-ICE-OCEAN INTERACTIONS AND THE DELAY OF AUTUMN FREEZE-UP IN THE WESTERN ARCTIC OCEAN

By Jim Thomson, Maddie Smith, Kyla Drushka, and Craig Lee



Preparing to recover a SWIFT buoy in the marginal ice zone from R/V *Sikuliaq* on September 30, 2020. *Photo credit: Alex de Klerk*

ABSTRACT. Arctic sea ice is becoming a more seasonal phenomenon as a direct result of global warming. Across the Arctic, the refreezing of the ocean surface each autumn now occurs a full month later than it did just 40 years ago. In the western Arctic (Canada Basin), the delay is related to an increase in the seasonal heat stored in surface waters; cooling to the freezing point requires more heat loss to the atmosphere in autumn. In the marginal ice zone, the cooling and freezing process is mediated by ocean mixing and by the presence of remnant sea ice, which may precondition the ocean surface for refreezing. The delay in refreezing has many impacts, including increased open ocean exposure to autumn storms, additional wave energy incident to Arctic coasts, shifts in animal migration patterns, and extension of the time window for transit by commercial ships along the Northern Sea Route. This article reviews the observed trends in the western Arctic and the processes responsible for these trends, and provides brief in situ observations from the Beaufort Sea that illustrate some of these processes.

INTRODUCTION

The dramatic decline in Arctic sea ice cover over the past several decades is one of the most striking impacts of our warming climate and goes hand-in-hand with substantial changes in the length and timing of the summer melt season. Sea ice has tended to melt earlier in summer and re-form later in autumn (Stroeve et al., 2014; Stroeve and Notz, 2018). As we approach the time when an ice-free Arctic summer is expected, the fraction of the ice pack undergoing autumn freeze-up is increasing (Druckenmiller et al., 2021). While just over 50% of the ice pack was seasonal ice in 1980, over 70% of the ice pack has been seasonal in recent years (when defined as the difference between the minimum and maximum extent, relative to the maximum ice extent; see Figure 1). Once the Arctic has an ice-free summer, 100% of the ice will be seasonal. This is likely by 2070 even under a moderate emissions scenario (Jahn et al., 2016), and earlier under a higher-emissions scenario (Docquier and Koenigk, 2021); an assessment based on the observational record predicts it will occur by 2050 (Stroeve and Notz, 2018).

This article focuses on the freeze-up that occurs each autumn, along with its spring and summer preconditions (Steele et al., 2015). The freeze-up process includes complex air-ice-ocean feedback mechanisms at multiple scales that make it difficult to accurately predict future Arctic scenarios (e.g., Wang and Overland, 2015). Out of these complexities, one simple rule is clear: sea surface temperatures (SSTs) must cool to the freezing point before sea ice can form. The paper thus begins with an overview of pan-Arctic trends in sea ice and sea surface temperatures from satellite data, and then explores processes specific to the western Arctic, where substantial changes have motivated recent in situ observations. Following the western Arctic focus, the remaining sections of the paper discuss the broader impacts of delayed freeze-up and identify key topics for future research.

Sea Ice Trends

The open water season is lengthening, with freeze-up occurring later in the autumn (Stroeve et al., 2014). From 1979 to 2010, the timing of ice advance as observed by satellite was delayed more than one month (Stammerjohn et al., 2012). There is high correlation ($R^2 \approx 0.8$) between earlier sea ice retreat (and hence greater ocean heat uptake during summer) and later sea ice advance. The timing varies based on the threshold of sea ice cover used to consider the ocean ice-covered. Peng et al. (2018) report a trend in the freeze-up, where sea ice crosses 80% concentration, that is stronger than the trend in sea ice onset, where sea ice crosses 15% concentration. The average freeze-up shift in that study is 6.5 days later each decade, computed over 1979 to 2017. In Figure 2c, we plot the linear trend of the Arctic freeze-up date, defined as the date when the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (Meier et al., 2021) exceeds 80%. Trends are only calculated for cells in which there are at least 10 valid freeze-up dates over the record (i.e., sea ice concentration must go below 80% during the summer and above 80% during the winter). Models can allow us to explore different definitions of freeze-up beyond sea ice concentration, such as SST, sea ice volume changes, and rates of congelation or frazil ice growth. The trend in delay is clear and significant regardless of what metric is chosen (Smith and Jahn, 2019), underscoring the robustness of the signal.

Freeze onset dates are likely to continue to shift later. Under the high-emissions RCP8.5 future scenario, the Community Earth System Model (CESM) global climate model large ensemble suggests that the delay will more than double by the end of the twenty-first century (Smith and Jahn, 2019). This suggests an additional 2.5-month delay in average

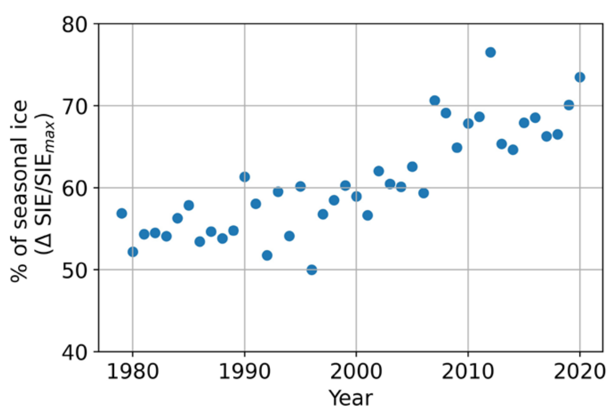


FIGURE 1. Percentage of Arctic sea ice extent (SIE) that is seasonal ice, defined as the difference between the minimum and maximum extent scaled by the maximum extent (Δ SIE/SIE$_{max}$), over the satellite record. Data from the National Snow and Ice Data Center (NSIDC) via https://doi.org/10.7265/N5GT5K3K.

pan-Arctic freeze onset by 2099 is possible. Though model predictions are dramatic, the actual delay may be even more severe, given the historical under-prediction of sea ice loss by climate models (Notz and Stroeve, 2016). As discussed below, observed and future changes in the timing of Arctic sea ice freeze-up are mostly a forced response to atmospheric and ocean warming, but feedbacks such as preconditioning due to early melt onset and local ocean-ice-atmosphere interactions likely also play a role.

Figure 2 shows substantial regional variability in the magnitude of the delay. Due to the geometry of the Arctic Ocean, the trends for delay in ice advance are even stronger in coastal zones of a particular area (Onarheim et al., 2018). For instance, in the Beaufort-Chukchi region, the ice advance along the coast portion has trended 1.2 days later per year through 2014, compared to 0.4 days later per year over the entire domain (Thomson et al., 2016).

Model studies show that the trend in freeze onset defined thermodynamically is stronger in open water areas than in those that remain partially ice covered (Smith and Jahn, 2019), suggesting the importance of feedbacks from solar ocean warming in driving these trends (Stammerjohn et al., 2012). In many coastal and fast ice regions, freeze-up timing is well predicted by melt onset timing, suggesting primarily thermodynamic factors (Stroeve et al., 2016). Freeze-up timing is also affected by mechanical dynamics, and thus storms make freeze-up progression less predictable (Polyakov et al., 2022).

Sea Surface Temperature Trends

Figure 3a–c shows increased sea surface temperatures (SSTs) across most of the Arctic, which have been widely reported (Steele et al., 2008) and that are clearly related to changes in solar absorption (Steele et al., 2010). While SST is a useful metric for tracking oceanic changes, it is important to note that SST does not necessarily represent the heat content of the upper ocean, which is far more important to the freeze-up process. Open-water summer SSTs averaged over 2010–2019 are 1°–2°C warmer at the seasonal maxima than they were in the 1980s, with

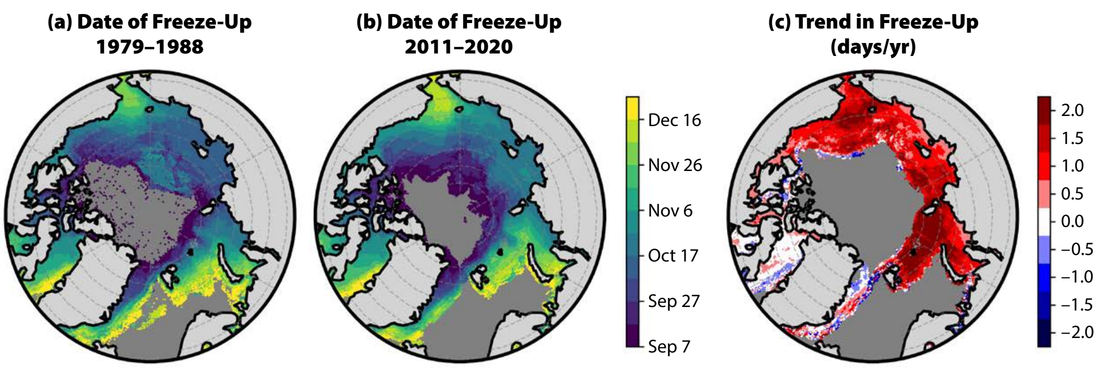


FIGURE 2. Date of sea ice freeze-up (a) averaged over 1979–1988 and (b) 2011–2020, and (c) the trend (days/yr) over 1979–2020. Freeze-up is defined as when sea ice concentration from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (Meier et al., 2021) exceeds 80%.

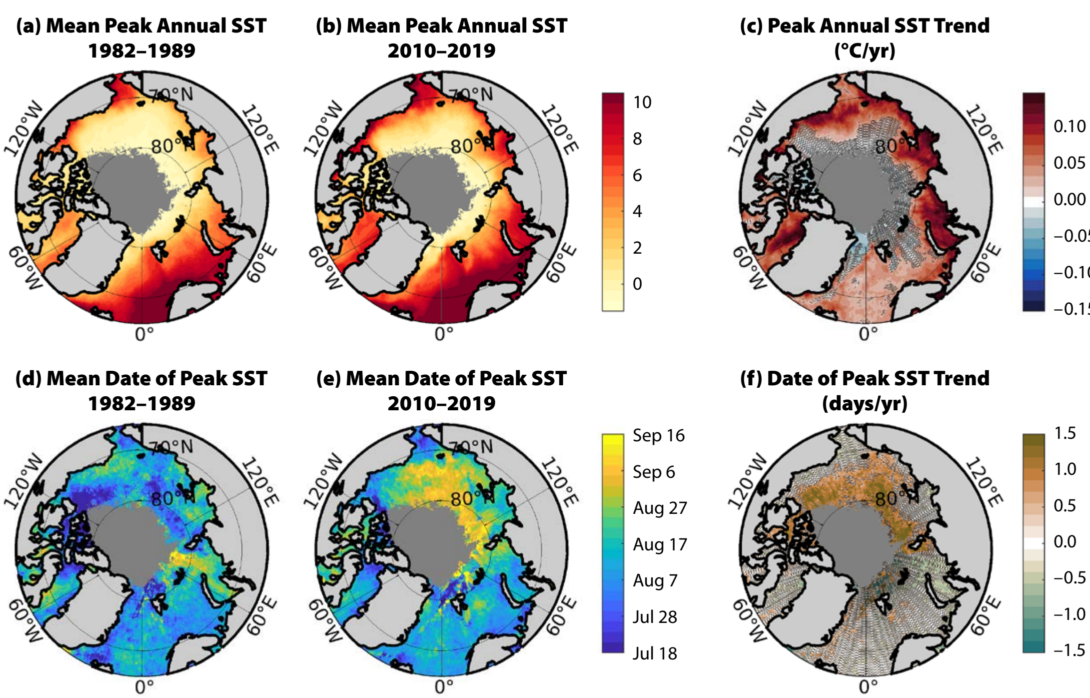


FIGURE 3. (top) peak annual sea surface temperature (SST) averaged over (a) 1982–1989 and (b) 2010–2019, and (c) the trend over the 1982–2020 time period. (bottom) Date of peak annual SST averaged over (d) 1982–1989 and (e) 2010–2019, and (f) the trend over the 1982–2020 time period. Data are from the NOAA High-resolution Blended Analysis of Daily SST (OISST) 0.25° product from 1982 to 2020. SST data with sea ice concentration (from the NOAA/NSIDC product) greater than 80% are masked prior to processing. Grid points for which fewer than 75% of years have sufficient ice-free data to compute a trend are masked in dark gray, and those for which trend is not significant at the 95% level are stippled.

the greatest changes seen south of 75°N. A widespread warming trend exceeding 0.1°C yr^{-1} is seen outside of the central Arctic Ocean and eastern Beaufort Sea (Figure 3c). In addition to warming, the timing of the annual peak SST (Figure 3d–f) has shifted significantly later in the year throughout much of the western Arctic. The warmest SSTs now occur in late August or early September, in comparison to the 1980s when SSTs peaked in late July (Figure 3d–f). In the Kara and Barents Seas, trends in annual peak SST are generally not significant. There are slight negative trends near the ice edge, which are an artifact of spatial averaging. The overall signal is an Arctic that is warmer in the autumn, with less and later sea ice as a direct result.

FREEZE-UP PROCESSES IN THE WESTERN ARCTIC

We now focus on the western Arctic and describe the dynamic and thermodynamic processes related to observed trends (Figure 4). In the western Arctic (Beaufort, Chukchi, and East Siberian Seas), trends in sea ice and SST are driven by inflow from the Pacific and by local heating; distinct water masses are important here (Nakanowatari et al., 2022). In the eastern Arctic marginal seas (e.g., Barents, Kara, and Laptev Seas), the key processes driving changes in SST and sea ice are quite different, including storm-driven upward transport of Atlantic Water heat and Atlantification, plus turbulent mixing above the continental slopes bordering Svalbard and Siberia. Eastern Arctic processes, which are beyond the scope of this paper, are discussed by Polyakov et al. (2017).

The cumulative decadal shifts in the western Arctic are illustrated by focusing on the month of October, the month that freeze-up has typically occurred and therefore the month in which long-term shifts in freeze-up are most clearly seen. Using the ERA5 reanalysis product, Figure 5 shows averages of October sea ice concentration, SST, and significant wave height from two decades:

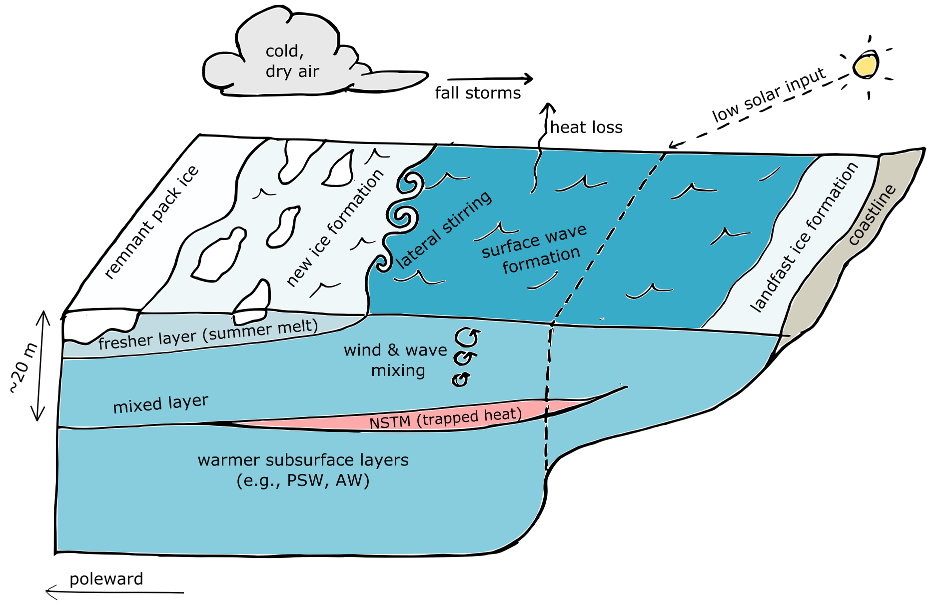


FIGURE 4. Schematic of key autumn freeze-up processes in the western Arctic. Storms generate wind and waves, driving heat flux out of the ocean that exceeds heat input from the sun, resulting in sea surface cooling and sea ice formation. Wind- and wave-generated mixing may also release heat trapped in the near-surface temperature maximum (NSTM), delaying freeze-up locally. In contrast, enhanced stratification from summer ice melt has the potential to sequester heat in the NSTM and hasten freeze-up.

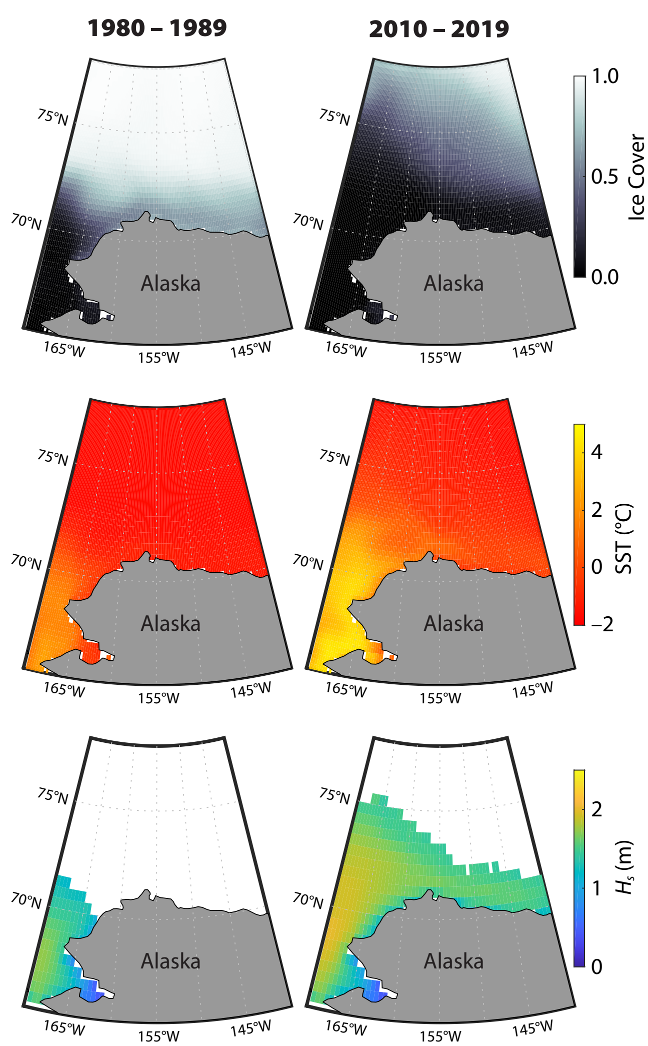


FIGURE 5. Average conditions for the month of October in the western Arctic from 1980–1989 (left) and 2010–2019 (right). Rows show sea ice concentration (top panel), sea surface temperature (SST, middle panel), and significant wave height (H_S, bottom panel) from the ERA5 reanalysis project, downloaded from https://cds.climate.copernicus.eu/.

1980–1989 and 2010–2019. The reduction in autumn ice cover is striking, as are the increases in SST and significant wave height. The relationship between SST and ice cover is thought to be both a cause and an effect, via the well-known ice-albedo feedback mechanism (Perovich et al., 2007). The increase in significant wave height is mostly a result of change in ice cover, which increases open-water fetch distances (Thomson and Rogers, 2014) and thereby increases wave heights, even in the absence of increasing winds (Thomson et al., 2016). Figure 5 suggests that the components of the air-ice-ocean system have combined to result in these seasonal shifts, each of which are explored in the following sections.

Heat Fluxes

Figure 4 shows the key processes in the autumn ice advance. The overall driver of ice formation is the loss of heat from the ocean to the atmosphere when large-scale atmospheric patterns bring cold air over warmer, open-water regions. As the input of solar heat decreases throughout the autumn, there are no external sources of heat to compensate for the loss to the atmosphere. There are, however, reservoirs of heat stored in the ocean. These reservoirs, discussed in more detail below, can reside below the surface because salinity controls stratification in most of the Arctic. Mixing controls the delivery of this stored heat to the ice-ocean interface, and thus its impact on ice formation. Upper ocean mixing is a complex interaction between processes that include direct forcing by surface winds and waves, lateral stirring by small-scale eddies and filaments, frontal dynamics, and internal ocean dynamics that generate vertical mixing, all of which are modulated by the strong near-surface stratification commonly found in this region (e.g., Brenner et al., 2020). As the freeze-up shifts later into the autumn, open water now coincides with stormier conditions and stronger upper ocean mixing (e.g., Smith et al., 2018).

Quantification of the processes in Figure 4 typically applies a surface heat budget, in which the rate of change in heat at the ocean surface is expressed in fluxes:

$$Q_{net} = Q_{sw} + Q_{lw} + Q_{sensible} + Q_{latent} + Q_{sub}. \quad (1)$$

Positive values represent heat gain by the ocean and negative values represent heat loss. In the autumn, the input (gain) from the net shortwave radiative term, Q_{sw}, diminishes, and the overall net, Q_{net}, generally becomes negative (loss). The longwave radiative term, Q_{lw}, is itself a net term that can change sign depending on cloud conditions and sea surface temperature. The rate of sensible heat lost to the atmosphere, $Q_{sensible}$, is controlled by the air-water temperature difference. The rate of latent heat lost to the atmosphere, Q_{latent}, is also a function of the temperature difference, along with the relative humidity of the air. Cold and dry air masses originating over the perennial ice pack are thus excellent sinks of heat when they pass over open water. The sensible and latent terms also depend strongly on wind stress, and estimation of these terms is thus further complicated by uncertainties in the atmospheric drag coefficient in partial ice cover (Andreas et al., 2010; Persson et al., 2018). A heuristic final term represents a rate of subsurface ocean heat (mostly from the near-surface temperature maximum, or NSTM; see later section on Upper Ocean Heat) mixing up to the surface, Q_{sub}, which represents a heat gain to the surface but a heat loss from the NSTM.

The flux terms in the surface heat budget (Equation 1) are typically calculated from observations using the COARE (Coupled Ocean-Atmosphere Response Experiment) algorithm; see Fairall et al., 1996, 2003). This algorithm uses bulk average observations to estimate terms that are primarily turbulence driven, such as $Q_{sensible}$ and Q_{latent}, and thus are rarely measured directly. Obtaining accurate estimates of these terms (and thus Q_{net}) in the Arctic remains a key challenge for both observational and modeling efforts.

The total net rate Q_{net} controls how fast the ocean surface cools in autumn, and, upon reaching a seawater freezing temperature of approximately −1.8°C, the rate of ice growth. The delay of autumn freeze-up is likely driven by a combination of adjustments to $Q_{sensible}$ and Q_{latent}, along with increases in Q_{sub}. The delay is also related to the simple truth that warmer initial sea surface temperatures must lose more heat (i.e., more sustained $Q_{net} < 0$) before reaching freezing temperature.

Atmospheric Forcing

Weather patterns are essential to autumn sea ice formation, especially in the western Arctic. Cold, dry air originating over sea ice can cause enormous sensible and latent heat loss from nearby open water regions (Persson et al., 2018). Thus, new ice growth is typically adjacent to the ice pack, and the progradation of the marginal ice zone is one common version of autumn freeze-up. Localized feedback mechanisms, such as low-level atmospheric jets that form along the ice edge (Guest et al., 2018), increase sensible and latent heat fluxes and potentially enhance vertical mixing.

Arctic air temperatures are increasing at rates about twice that of global warming (e.g., Serreze et al., 2009; Bekryaev et al., 2010; Dai et al., 2019). The effect on heat fluxes is significant. In areas with newly open water, there is much greater exchange between the ocean and the atmosphere (because the air-water temperature differences are larger). In areas that already had open water, the sensible heat losses are reduced. More specifically, the Arctic amplification observed in the warming trend is strongest in autumn and winter (Serreze and Barry, 2011; Dai et al., 2019). The reduction in cold air in autumn and the reduced rates of heat loss from the open ocean to the atmosphere are clear drivers for the delay of autumn freeze-up.

Atmospheric forcing also indirectly affects autumn freeze-up. Patterns in surface winds drive ocean circulation, which in turn affect the distribution of ocean temperatures. This can be particularly important at regional scales. For example, an episodic shift in atmospheric circulation over the Bering Sea in 2018 increased the transport of warm water into the Chukchi Sea and delayed freeze-up that year (Kodaira et al., 2020). Wind-driven advection of sea ice also affects patterns of melt and freeze-up. Both these indirect and the direct mechanisms connect climate-scale atmospheric patterns to seasonal ice extent (Cai et al., 2021).

Autumn weather in the western Arctic is quite active, with cyclones forming and passing regularly through the region (Pichugin et al., 2019). Several studies have suggested that Arctic cyclones cause sea ice retreat in summer/autumn, as in the Great Arctic Cyclone of 2012 (Simmonds and Keay, 2012). However, recent work shows more nuanced effects, in which Arctic cyclones decrease ice in the eastern sector of the storm (where the air is warm and moist) and increase it in the storm's western sector (where the air is cold and dry; Clancy et al., 2021). The same work argues for equal importance of dynamic (i.e., motion) and thermodynamic (i.e., heat) effects on sea ice from Arctic cyclones. Looking to the future, there are clear linkages between the loss of ice and the large-scale atmospheric patterns (Moore et al., 2018; Ballinger et al., 2021; Valkonen et al., 2021). We can thus expect the atmosphere to continue to enhance delays in autumn freeze-up.

Upper Ocean Heat

Upper ocean heat content and the processes that deliver heat to the ice-ocean boundary layer modulate the timing and location of sea ice formation. Autumn freeze-up proceeds as waning shortwave radiation and colder air temperatures drive increased heat flux from the ocean surface layer into the atmosphere. During summer, solar input ($Q_{sw} + Q_{lw}$) is the dominant source of heat to the upper ocean (e.g., Maykut, 1982; Maykut and McPhee, 1995; Shaw et al., 2009). Once the solar input fades in autumn, cooling at the ocean surface is assured.

Strong surface layer freshening (McPhee et al., 1998; Solomon et al., 2021) has accompanied increased mixed layer temperatures in recent decades (Peralta-Ferriz and Woodgate, 2015), and is associated with changes in river runoff, precipitation, and sea ice melt or export (Haine et al., 2015). In the western Arctic, increasingly fresh inflow through the Bering Strait likely also plays a role (Woodgate and Peralta-Ferriz, 2021). At the cold temperatures (<5°C) typical of the Arctic upper ocean, seawater density is controlled primarily by salinity. Surface layer freshening thus strengthens the cold halocline, reinforcing the strong stratification that can isolate warmer waters below the mixed layer from the ice-ocean boundary layer above, enhancing surface cooling and promoting sea ice growth. This process can be patchy, with significant spatial variability (e.g., MacKinnon et al., 2021)

After the late-summer decrease in solar heat input each year, subsurface reservoirs of warm water, which are isolated from the ice-ocean boundary layer by the colder and fresher waters above, become the primary source of heat to the ice-ocean boundary layer. Atlantic waters that enter through Fram Strait and the Barents Sea circulate throughout the Arctic and represent the largest source of heat, though in the western Arctic these are too deep to provide much heat to the surface layer. The western Arctic typically exhibits two shallower, and thus more accessible, reservoirs of relatively warm waters. The shallowest, most accessible reservoir of heat is the NSTM (Jackson et al., 2010, 2011), which is typically found around 20 m to 30 m depth and is formed seasonally from surface waters that have been warmed by solar radiation and then capped by fresher, colder, more buoyant waters associated with sea ice melt (e.g., McPhee et al., 1998; Perovich et al., 2008). The NSTM provides short-term storage for summertime heating that is shallow enough to be released to the ice-ocean boundary layer by vertical mixing later in the autumn (e.g., Smith et al., 2018).

Pacific Summer Water (PSW) provides a second reservoir of heat in the western Arctic that is both larger and deeper (>40 m) than the NSTM. In summer, Pacific waters enter the Arctic through the Bering Strait (Woodgate, 2018), warming as they flow over the Chukchi Sea Shelf before they subduct below the fresher, more buoyant surface waters of the Beaufort Gyre (Timmermans et al., 2014). Subsurface eddies (Spall et al., 2008; Fine et al., 2018) and filaments (MacKinnon et al., 2021) inject these warm waters into the interior halocline. PSW is found throughout the Canada Basin (Timmermans et al., 2014) and has been associated with episodes of anomalous sea ice retreat over the Chukchi Sea and the southern Canada Basin (Shimada et al., 2006; Woodgate et al., 2010). Even in autumn, when cold air increases sensible heat loss, the PSW does not cool much before it subducts (and becomes isolated from the atmosphere). Thus, PSW is a source of heat to the region that arrives via a lateral process, but the effects of this heat are limited by vertical processes and may not have large basin-wide impacts on short (sub-seasonal) timescales. The PSW reservoir sits between 40 m and 100 m depth, within the cold halocline. Upper ocean stratification and diapycnal mixing exert strong control on the ability of PSW to supply heat to the ice-ocean boundary layer. In addition to the persistent water mass, pockets of anomalous PSW heat can persist for months to years within eddies moving through the region at the base of the mixed layer (Fine et al., 2018).

Lateral processes may also play an important role in the delivery and distribution of stored oceanic heat, especially along the marginal ice zone (MIZ; Manucharyan and Thompson, 2017). Energetic submesoscale turbulence can generate strong lateral stirring of heat and sea ice, as well as divergences with upwelling that can carry warm water to the surface locally. These are further enhanced by local winds and ice motion, which alter the otherwise persistent lateral gradients (Brenner et al., 2020). These processes can drive rapid restratification (e.g., Boccaletti et al., 2007; Thomas et al., 2008; Timmermans et al., 2012) and likely modulate NSTM formation throughout summer and autumn. In some cases, fresh surface layers from ice melt may have sufficient stratification to inhibit mixing and thereby hasten sea ice formation by preconditioning the surface (Crews et al., 2022). This is an active area of research, with a large field campaign planned for autumn 2022 to sample stratification and surface fluxes near the autumn ice edge (https://salinity.oceansciences.org/sassie.htm).

Observations of an Autumn Ice Edge

In situ observations near the ice edge in the Beaufort Sea on September 30, 2020, illustrate many of the key processes that delay or accelerate ice formation during the initiation of freeze-up in the western Arctic. These observations are applied for estimating Q_{net} using the COARE algorithm and for demonstrating the net balance that cools the ocean surface in autumn. The data presented here were collected opportunistically as part of a transit leg during the 2020 mooring recovery cruise for the Coastal Ocean Dynamics in the Arctic (CODA) program (http://www.apl.uw.edu/CODA). The observations span a marginal ice zone formed by remnant ice that had persisted in the southern Beaufort Sea for the entire summer of 2020. The overall minimum ice extent occurred on September 15, so these observations were made during the early stages of that year's large-scale freeze-up.

The observations were collected in an ice-following reference frame, spanning open water to nearly complete ice cover. Drifting buoys were used to establish the ice-following reference frame, which aids in diagnosing the evolution of temperature and salinity as purely temporal. Previous studies have used this approach to reduce the complications of interpreting changes that occur as ice advects through a spatial field (Smith et al., 2018; Brenner et al., 2020). Here, four Surface Wave Instrument Float with Tracking (SWIFT; see Thomson, 2012, for description of the platform) buoys were deployed to freely drift for one day, while R/V *Sikuliaq* followed the drift and collected temperature and salinity profiles. Figure 6 shows the region of the sampling, along with an image of a SWIFT drifter in the ice. The practical salinity scale is used throughout (IOC, SCOR, and IAPSO, 2010).

The right panels of Figure 6 show the average salinity and temperature profiles collected in the ice and in open water, along with surface values from the SWIFTs. Although only separated by 6 km, the profiles in Figure 6 are notably different and demonstrate the preconditioning that influences freeze-up timing. As is typical for the MIZ, the surface waters in the ice are cold and fresh, relative to open water. However, even in broken ice, the SST is well above the nominal seawater freezing point of 1.8°C. Thus, heat loss Q_{net} must continue to occur before the MIZ refreezes into solid ice cover. The broken ice here is still melting, albeit slowly, until the freezing temperature is reached. The subsurface waters are the more notable part of this data set. The profile in open water has a strong NSTM around 10 m, relative to the weaker signal for the profile in the ice. It is expected that this NSTM resulted from the solar heating accumulated throughout the summer followed by surface cooling in the early autumn and possibly advected meltwater. Within the ice, the NSTM is thinner, weaker, and shallower because the higher albedo of partial ice cover has minimized the accumulation of solar heating during the summer.

The NSTM in open water is a reservoir of heat that can be released by ocean mixing (becoming Q_{sub}) to create large changes in Q_{net} that can delay the freeze-up by days and even weeks. Given the same atmospheric forcing, the area of broken ice is likely to refreeze much faster than the open water 6 km away. This would be true even without the difference in the surface temperatures, because

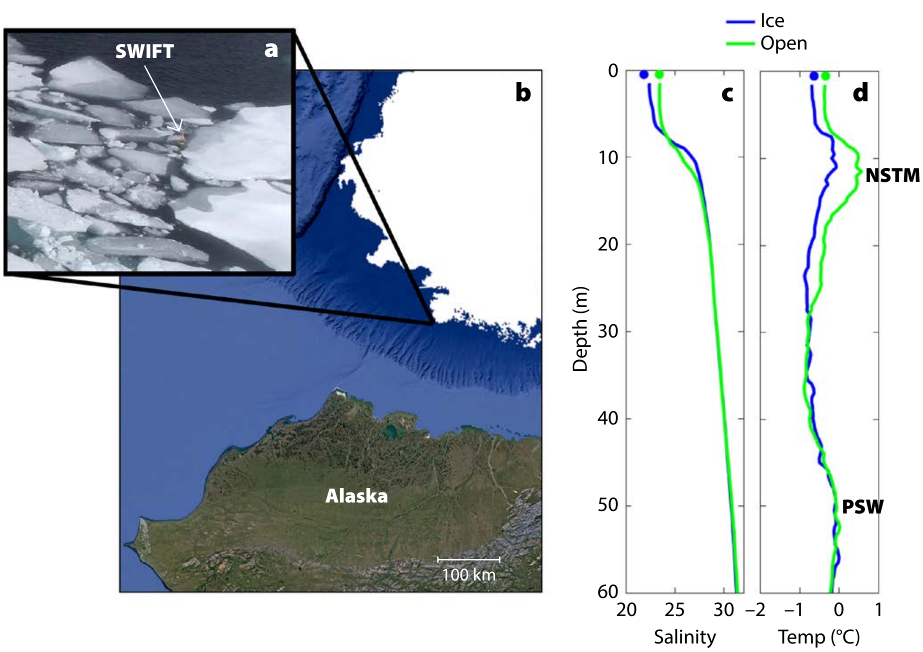


FIGURE 6. Data collection in the marginal ice zone of the Beaufort Sea on September 30, 2020. (a) Aerial image of the ice edge, in which a SWIFT drifter was sampling. *Image credit: Alex de Klerk* (b) Map showing ice cover (white) with sampling location. (c) Salinity profiles. (d) Temperature profiles. The surface points shown at the top of the profiles were measured by the SWIFT drifters, and the profiles were collected by shipboard CTD casting with a lateral separation of 6 km. PSW = Pacific Summer Water. NSTM = Near-surface temperature maximum. Ice cover from NSIDC via https://doi.org/10.7265/N5GT5K3K.

the total integrated heat of the NSTM will provide a Q_{sub} that controls Q_{net} in open water. Applying a seawater heat capacity of 3,850 J kg^{-1} C^{-1} to the temperature profiles in Figure 6, the open water profile has 4.2×10^7 J m^{-2} more heat than the profile in the ice. It would take 4.4 days of continuous heat loss at $Q_{net} = -100$ W m^{-2} for the open water profile to arrive at the same heat content as the profile in the ice (assuming no change in the ice profile). Lacking observations of the evolution of these profiles, we can only speculate that the actual heat loss is much more complicated, as Q_{net} varies over both profiles and some difference between them persists for weeks or more.

The speculated evolution toward freezing in this example becomes more quantitative upon estimating the heat fluxes (Equation 1) on the day the profiles were collected. Using the COARE algorithm (Fairall et al., 1996, 2003), the primary inputs are: air and water temperatures, relative humidity, wind speed, and radiation. The observed air temperature (−2°C) is always lower than the water temperature, leading to a steady loss of heat at the surface that is large in open water due to the stronger air-sea temperature gradient ($Q_{sensible} \sim -50$ Wm^{-2}). During daylight hours, the peak incoming shortwave radiation (Q_{sw} up to +150 W m^{-2}) exceeds this sensible heat loss and there is a brief net gain of heat in open water. The brief positive daytime surface flux is the lingering signal of the summer heating that originally formed the NSTM. This only occurs over open water; the albedo over the broken ice is much higher, and the net flux remains negative there. This brief example is representative of the early autumn ice edge, where spatial gradients modulate the heat fluxes as water temperatures evolve toward the freezing point. Recent work of Crews et al. (2022) uses autonomous systems to observe the full evolution of a similar region and provides a more comprehensive example.

Finally, we note the presence of PSW as secondary temperature maxima around 50 m in both profiles. As this is the result of inflow from Bering Strait, it is much more uniform across the region and does not have the kilometer-scale variation of the NSTM at the ice edge. Although the PSW does have a significant amount of total heat, it is generally too deep to mix up to the surface and affect Q_{net} on subseasonal timescales.

DISCUSSION

Feedbacks and Coupled Processes

Estimation of the heat fluxes that determine cooling and freeze-up is challenging. The COARE algorithm used to estimate fluxes in the prior section was originally developed for the tropics and has only sparse verification in the Arctic (Persson et al., 2018). The algorithm lacks explicit treatment of polar processes, such as heat loss from freezing spray (Blackmore and Lozowski, 1993) and changes to the atmospheric drag coefficient based on ice cover (Andreas et al., 2010). These processes need to be understood well enough that they can be formulated in robust parameterizations and then applied in predictive models.

The unsteady and heterogeneous nature of these coupled processes makes parameterization particularly challenging. The atmospheric drag coefficient that controls the flux of momentum from the atmosphere to the ocean (and/or sea ice) is sensitive to the stability of the lower atmosphere, which can change rapidly near the ice edge (Guest et al., 2018). Similarly, the ice drag coefficient that controls the flux of momentum from sea ice to the ocean below is sensitive to ice fraction and geometry (Tsamados et al., 2014; Brenner et al., 2021). Changes to momentum flux affect mixing and, thereby, fluxes of heat.

As discussed, prior melting in the marginal ice zone has a stabilizing effect, via salinity stratification, that can trap heat in the NSTM. Whether this heat can be mixed to the surface (and thus adjust Q_{net}) depends on the momentum flux through the stratified surface layer. Models require accurate drag coefficients to predict this process, and those drag coefficients evolve as well (i.e., depend on ice concentration, wind speed, atmospheric stability). Coupling air-ice-ocean models is becoming routine (Bromwich et al., 2018), but the uncertainty related to momentum and heat flux coefficients remains significant (Martin et al., 2016).

Surface waves have not been traditionally considered a key part of the coupled Arctic air-ice-ocean system, but surface wave activity in the Arctic is increasing (Wang et al., 2015; Stopa et al., 2016; Thomson et al., 2016) as a direct result of sea ice reduction (Thomson and Rogers, 2014). Not only are the open water fetch distances greater, but it is now more likely for open water to persist well into the autumn, when storms increase in frequency and severity. Even in partial ice cover, wave growth is a function of fetch and is increasing (Smith and Thomson, 2016; Gemmrich et al., 2018). The possible feedbacks between the waves and the ice are numerous, and the large-scale implications remain an active area of research.

Recent modeling efforts include two-way coupling of wave-ice evolution (Williams et al., 2017), in which waves can alter the prognostic floe size distribution of sea ice and sea ice attenuates waves across the whole Arctic (Roach et al., 2019). Such mechanisms would tend to exacerbate ice loss by providing more lateral melting of broken floes. Other processes, such as enhanced upward mixing of ocean heat caused by Langmuir turbulence, have also been shown to cause ice loss (Smith et al., 2018). Conversely, waves can enhance ice growth in the formation of pancake ice (Roach et al., 2018), which has become a more prevalent ice type in the Arctic in recent years (Thomson et al., 2018; Nose et al., 2020).

Impacts of Delayed Freeze-up

The dramatic delay in the autumn return of sea ice across the Arctic has numerous impacts beyond purely geophysical processes. Changes to Arctic coastal environments, to ecosystems, and to human use patterns provide a few examples.

One of the most notable impacts of more open water in the autumn is an increased wave climate. Figure 7 uses the ERA5 reanalysis product to demonstrate the increase in wave activity across the western Arctic. For the domain shown in Figure 5, the sum of the wave energy throughout the month of October is increasing. There is also significant interannual variability, including the remarkable persistence of open water in 1998 (Maslanik et al., 1999). The overall signal is a transition from an October that was nearly devoid of waves in the 1980s to one that is now very active. It is clear that this is a consequence of the delay in autumn freeze-up, which a few decades ago was nearly complete by the beginning of October (Figure 5).

The systematic delay of the autumn freeze-up means that Arctic coasts are exposed to more open ocean storms, which cause erosion and flooding (Overeem et al., 2011). The risk to permafrost coastlines is particularly severe, with Alaskan coastlines identified as highly vulnerable and already manifesting shoreline retreat rates of several meters per year (Irrgang et al., 2022). The pan-Arctic shoreline loss is 0.5 m yr^{-1} (Lantuit et al., 2012), and the northern Alaska rate is 1.4 m yr^{-1} (Gibbs et al., 2015, 2019). The presence of landfast ice does provide protection for the coasts (specifically from wave-driven processes), but that protection is preferentially in the spring (Hŏseková et al., 2021). In the autumn, newly forming ice along the coast is generally less effective in protecting the coast from wave-driven processes (Hŏseková et al., 2020).

Rolph et al. (2018) examine the freeze-up trends of three Alaskan Arctic coastal communities and find delays of approximately one month in the date of freeze-up for communities exposed to the open ocean. Additionally, there has been an increase in the number of "false freeze-up" events, which suggests an increase in the length of time during which communities are left without reliable ocean transport, as the ocean is neither suitable for boating nor frozen enough for on-ice travel. Various studies indicate that this problem will increase in the coming years (e.g., Casas-Prat and Wang, 2020).

In addition to changes in subsistence hunting and harvesting near the coasts, there are changes to human use patterns farther offshore. Interest in northern sea routes for commercial shipping has increased in recent years (Showstack, 2013), as have security concerns (US Navy, 2014, 2019). Already, there are estimates of conditions for commercial shipping in an ice-free Arctic (Nose et al., 2018). It is reasonable to expect that there will be more ship traffic as a direct consequence of a longer open-water season and less ice overall.

There are also changes to the Arctic ecosystem associated with delays in autumn freeze-up, including the northward shift of habitats and delays in migration (Baker et al., 2020). For example, recent work shows that polar cod, an essential part of the Arctic food web, are preferentially found beneath newly forming sea ice in autumn (Flores et al., 2020). Later ice thus means later polar cod, as well as the possibility of late autumn phytoplankton blooms (Ardyna et al., 2014). The long-term fate of larger animals, such as polar bears, is also clearly tied to sea ice trends (Regehr et al., 2016). For the Indigenous communities with ongoing subsistence practices, these ecosystem impacts are human impacts too. See Huntington et al. (2022) for a more complete description of the changes and challenges faced by local communities.

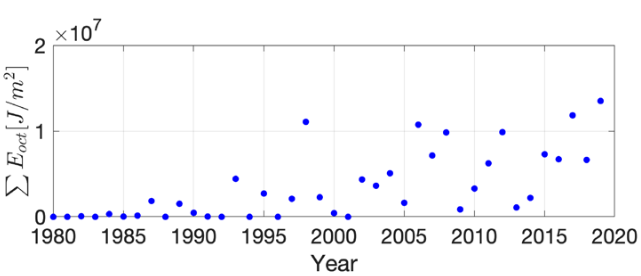


FIGURE 7. Cumulative wave energy in the western Arctic (region defined in Figure 5) from each October 1979–2020, based on ERA5 reanalysis data.

CONCLUSIONS

The autumn ice advance in the Arctic is happening later and later in the year, as part of a larger shift in the annual cycle of a warming planet. The trend is clear, even though many aspects of the relevant processes are still to be revealed. The seasonal ice advance is not a linear march southward as solar radiation declines. Rather, it is the evolution of a system controlled by atmospheric forcing, ocean memory, and multiple feedback mechanisms on both local and larger scales.

For the western Arctic Ocean (Canada Basin), the present state of knowledge about processes affecting delayed autumn freeze-up can be summarized as follows:

- There is an increased accumulation of ocean heat during summer months as a result of warming air temperatures and solar radiation.
- Ocean mixing events (i.e., storms) release subsurface heat in the autumn and thereby delay freeze-up.
- Strong lateral gradients and instabilities present at the evolving ice edge modulate the mixing events.
- The ocean can be preconditioned to refreeze by the presence of remnant sea ice.
- There is strong coupling at the atmosphere-ocean-ice boundary, including possible feedback mechanisms related to surface wave action.

It is highly certain that the delay in freeze-up will continue and grow, yet there is more work to be done in understanding the coupled processes that drive both freeze-up and its delay. To advance the state of knowledge, and to improve model predictive skill, we identify several needs for future work, including:

- Understand the drivers and impacts of near-surface (0–5 m) stratification during freeze-up.

- Determine the importance of lateral shear and associated mixing near the evolving ice edge.
- Develop a polar-specific version of the COARE algorithm to estimate bulk air-sea fluxes in the presence of sea ice, including improved parameterizations (e.g., drag coefficients) for air-sea exchanges of heat and momentum rather than coupling.
- Refine fully coupled atmosphere-ocean-ice models that include possible feedback mechanisms with surface wave activity.

Addressing these needs will require distributed observations of autumn freeze-up across the Arctic, especially sustained observations at or near the ocean surface. Autonomous platforms offer a promising approach to collecting data near the surface interface with minimal disturbances, but they present challenges in endurance and navigation (Meinig et al., 2015; Lee and Thomson, 2017; Zhang et al., 2019; Grare et al., 2021). Despite numerous recent and ongoing field efforts, there remains a gap in the observations needed to calibrate and validate heat flux estimates. These recommendations seek both to improve the accuracy of predictive models and to improve fundamental understanding of the Arctic system.

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SIDEBAR > THE ARCTIC RADIUM ISOTOPE OBSERVING NETWORK (ARION)

TRACKING CLIMATE-DRIVEN CHANGES IN ARCTIC OCEAN CHEMISTRY

By Lauren Kipp and Matthew Charette

The transport of elements from terrestrial sources to the open ocean is particularly important in the Arctic, where continental shelves comprise half the ocean area (Jakobsson, 2002) and over 10% of the world's river water is discharged (McClelland et al., 2012). Climate change is further increasing land-ocean exchange by thawing permafrost, increasing river discharge, and enhancing coastal erosion (Günther et al., 2013; Moon et al., 2021).

Radium (Ra) is constantly produced through the decay of thorium isotopes in sediments, and it is soluble in seawater, so coastlines, continental shelves, and benthic sediments act as sources of Ra to the water column. Thus, Ra isotopes are powerful tracers of terrestrial-derived elements and can be used to track shifts in the chemistry of the Arctic Ocean that may be driven by climate change. Higher levels of Ra in surface waters are indicative of a more significant input of elements from coasts and continental shelves (Kipp et al., 2018; Rutgers van der Loeff et al., 2018). Although Ra itself is not biologically utilized, it acts as a quasi-conservative tracer for sediment- and porewater-derived nutrients such as carbon and trace metals (Charette et al., 2020).

To better understand if and how climate warming is driving an increased flux of shelf-derived materials to the Arctic Ocean, we established the Arctic Radium Isotope Observing Network (ARION). This combined shipboard and mooring-based observational program, supported by the US National Science Foundation's Office of Polar Programs (NSF-OPP) Arctic Observing Network, will allow us to collect seasonal and interannual time-series measurements of radium isotopes in Arctic surface waters. Such a high-resolution record will make it possible to distinguish climate-related changes in shelf-derived material fluxes from seasonal changes (e.g., river inputs, water column overturning) and natural variability (e.g., Arctic Oscillation). We are particularly interested in monitoring the levels of Ra-228 in the Transpolar Drift (TPD), a strong surface current that carries river- and shelf-influenced waters from the East Siberian and Laptev Seas across the central Arctic (**Figure 1a**). Radium will serve as a tracer for other biologically important elements that are transported in the TPD, such as dissolved organic carbon, iron, and copper (Charette et al., 2020).

The first goal of the ARION program, to establish a seasonal time series, will be accomplished using novel Moored Radium In-situ Samplers (MoRIS) developed through a collaboration with McLane Research Laboratories Inc. Samplers will be deployed on two moorings located on the slopes of the Laptev and East Siberian Seas, where the TPD originates, and will collect monthly samples over a two-year deployment (**Figure 1b**). Year-round monthly sampling by MoRIS will fill the research gap that currently exists due to the prohibitive logistical challenges of conducting sampling in the Arctic during seasons with high sea ice coverage. Most of our understanding of Arctic Ocean chemistry comes from shipboard surveys during the Arctic summer months; MoRIS will help provide context for these data.

The seasonal time series will be supplemented by biennial surface water sampling of Ra isotopes in the TPD along the East Siberian and Laptev Sea slopes, extending the existing record (which currently consists of four time points in 1994, 2007, 2011, and 2015) through 2025. Such a long-term assessment is required to determine if Arctic Ocean chemistry is shifting in response to rising temperatures. In addition to monitoring the absolute levels of Ra isotopes, we will use Ra isotope ratios, water isotopes, and water mass modeling to distinguish between different drivers of change, such as increased river discharge, increased shelf sediment inputs, or increased influence from Atlantic- or Pacific-derived waters.

These project goals will be accomplished through a collaboration with the Nansen and Amundsen Basins Observational System (NABOS), another NSF-OPP funded program that has been monitoring the physical oceanography of the eastern Arctic since the early 2000s (Pnyushkov and Polyakov, 2022, in this issue). The first TPD survey and MoRIS deployment took place on a NABOS-led cruise in fall 2021. In 2023, we will recover the monthly samples collected by MoRIS, redeploy the samplers for another two-year period, and add another time point to the surface water monitoring. In 2025, the second set of monthly samples will be recovered, and surface water Ra levels will be measured again. The physical oceanographic data collected by the NABOS team will complement our isotopic measurements, ensuring that our results will be of use to a broad audience.

ARION also includes international collaborators, who will collect water samples for Ra isotopes in the nearshore shelf environment and elsewhere in the Arctic basin. These measurements will provide information about the upstream and downstream TPD endmembers and widen the reach of our observing network.

Through ARION, we aim to improve our understanding of how climate change is impacting the chemistry of the Arctic

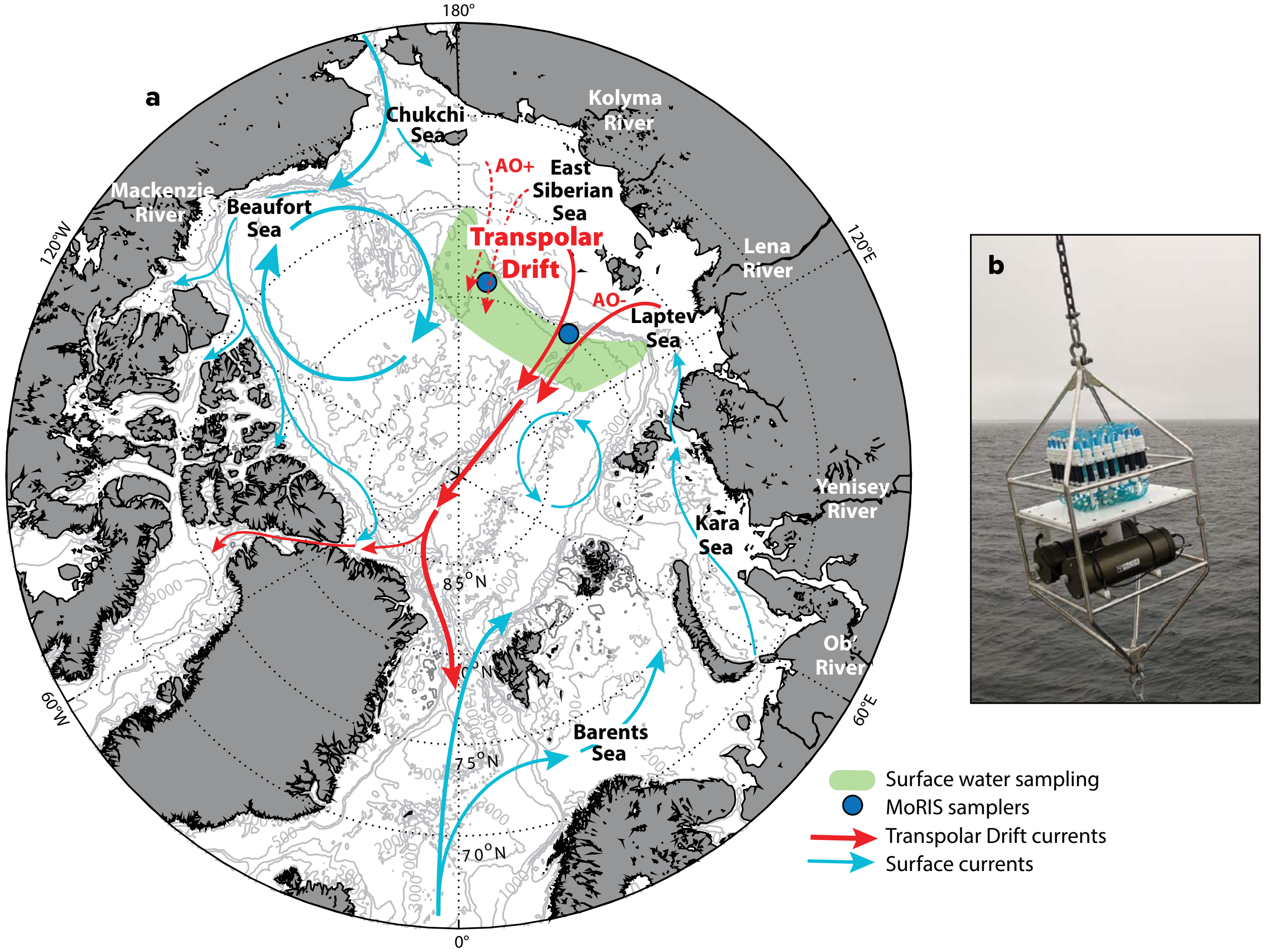

FIGURE 1. (a) Map of the Arctic Ocean showing the approximate region of surface water sampling (green shading) and locations where Moored Radium In-situ Samplers (MoRIS) will be deployed (blue circles). Red arrows show approximate paths of the Transpolar Drift surface current, with dashed and solid lines indicating the origin under positive (AO+) and negative (AO–) modes of the Arctic Oscillation, respectively. Blue arrows indicate other upper ocean circulation features. (b) Photo of a MoRIS during deployment on the Laptev Slope in fall 2021.

Ocean and how fast those changes are occurring. This knowledge will in turn improve predictions of the biological consequences of the changing climate, not only in the Arctic but also in the downstream North Atlantic.

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SIDEBAR > NANSEN AND AMUNDSEN BASINS OBSERVATIONAL SYSTEM (NABOS)

CONTRIBUTING TO UNDERSTANDING CHANGES IN THE ARCTIC

By Andrey V. Pnyushkov and Igor V. Polyakov

On September 2, 2002, the Nansen and Amundsen Basins Observational System (NABOS) program deployed its first mooring in the Eastern Eurasian Basin (EEB) of the Arctic Ocean. Since then, NABOS moorings, complemented by repeat multidisciplinary shipborne surveys and Lagrangian drifters (**Figure 1**), have provided a unique data set in an area of traditionally sparse observations. A series of moorings placed at several strategically important locations continues to be the program's primary monitoring tool for capturing major near-slope mass, heat, and salt transports and their links to lower-latitude processes. These data will aid in quantifying shelf-basin interactions, documenting water mass transformations, and understanding key mechanisms that lead to the Arctic Ocean's variability. International collaboration, particularly among the eight Arctic countries, has been an essential part of this observational strategy, with researchers from 18 counties taking part in NABOS cruises since 2002.

This observational strategy has paid off well. For example, data collected from the NABOS mooring in 2004 showed a strong warming signal in the warm (temperature >0°C) and salty waters of Atlantic origin (Atlantic Water, AW), suggesting that the eastern Arctic Ocean is in transition toward a new, warmer state (Polyakov et al., 2005). Moreover, NABOS mooring data collected in 2006 in the vicinity of Svalbard at ~30°E showed AW temperature anomalies unprecedented in the history of regional instrumental observations (Ivanov et al., 2009). Concerted efforts of the international team of scientists from the United States, Germany, Russia, and Norway provided evidence that this anomaly took about 1.5 years to propagate from the Norwegian Sea to the Fram Strait region, and it took an additional 4.5 to 5 years to reach the EEB slope. NABOS mooring observations also revealed the structure of the boundary current, showing a sixfold decrease of the current's speed on the route from Svalbard to the central Laptev Sea (Pnyushkov et al., 2015). NABOS repeat oceanographic transects confirmed the ongoing large-scale warming of the EEB. Furthermore, combined with data provided by other projects, they showed that the warm anomaly found its way further eastward towards the Canadian Basin (**Figure 2**). This warm pulse peaked in 2007–2008. By the late 2000s, the ocean interior had become slightly cooler (by 0.07°C) relative to the peak years, but still remained much warmer (by ~1°C) compared to the climatology of the 1970s (Polyakov et al., 2012).

Enhanced mooring capabilities of the program in the 2010s were critical in documenting and understanding further dramatic changes in the polar basins. These changes are closely related to the progression of anomalies from the Atlantic sector of the sub-Arctic seas into polar latitudes—a process called "Atlantification" (Polyakov et al., 2017). These observed

FIGURE 1. (left) R/V *Akademik Tryoshnikov* conducting operations during the 2021 Nansen and Amundsen Basins Observational System (NABOS) cruise. (right) Deployment of an Ice-Tethered Profiler in the eastern Arctic Ocean in October 2021.

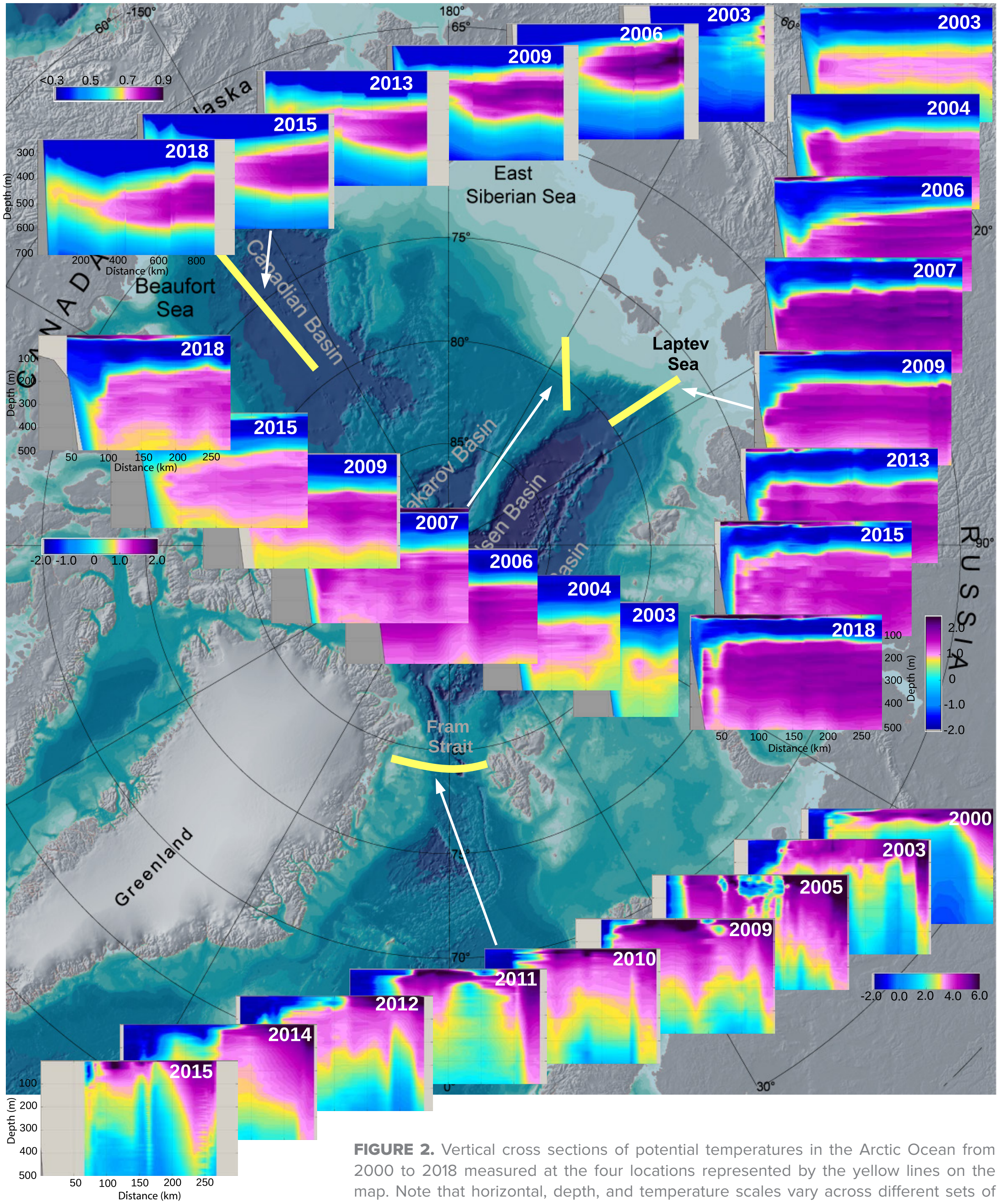

FIGURE 2. Vertical cross sections of potential temperatures in the Arctic Ocean from 2000 to 2018 measured at the four locations represented by the yellow lines on the map. Note that horizontal, depth, and temperature scales vary across different sets of cross sections. The temperature transects enable tracing of warm pulses associated with Atlantic Water (AW) warming along the trajectory of AW propagation from the Fram Strait through the Canada Basin. In the Eastern Eurasian Basin (EEB), the first signatures of AW warming were registered by NABOS observations in 2004 (Polyakov et al., 2005). The warm AW pulses peaked in the Eurasian Basin in 2007–2008. Afterward, the thermal regime of the EEB stabilized, suggesting that a pulse-like regime of AW warming typical for the early 2000s has changed to a regime with permanently high AW temperatures. *Updated from Polyakov et al. (2011)*

changes represent a shift toward EEB conditions that resemble those observed in lower latitude regions—that is, warmer water with weaker vertical stratification in the upper ocean. At the same time, 2013–2018 NABOS mooring observations showed a lack of strong changes in the intensity of EEB alongslope water transports, suggesting that eastern Arctic Ocean Atlantification is related to changes in salinity at upstream locations in the Barents Sea (Pnyushkov et al., 2018, 2021).

The consequences of the reduced upper ocean stratification in the EEB are manifold. Both regional CTD surveys and mooring observations provide strong evidence of enhanced winter ventilation (Figure 3). For example, the CTD observations suggest an increase in winter (February–April) mixed layer depth—a robust indicator of winter mixing—in the 2010s compared to 1970s climatology (Figure 3, right). NABOS 2013–2018 mooring observations captured complete erosion by winter convection of the stratified layer (called Cold Halocline Layer, CHL) that buffers the upper ocean and sea ice from the warmth of the AW (Figure 3, left). Deep penetrative ventilation of the upper ocean well beyond the surface mixed layer strongly suggests an important role for entrainment rather than slow, molecularly driven, double-diffusive mixing in the upper EEB. This deep winter ventilation has resulted in enhanced upward AW heat fluxes sufficiently large to contribute substantially to the diminished regional sea ice cover (Polyakov et al., 2017, 2020b).

Using 2004–2018 mooring observations from the upper 50 m layer in the EEB, Polyakov et al. (2020c) revealed increased current speeds and shears associated with greater coupling between wind, ice, and oceanic currents and their vertical shear, particularly in summer. Substantial increases in both current speeds and shears are dominated

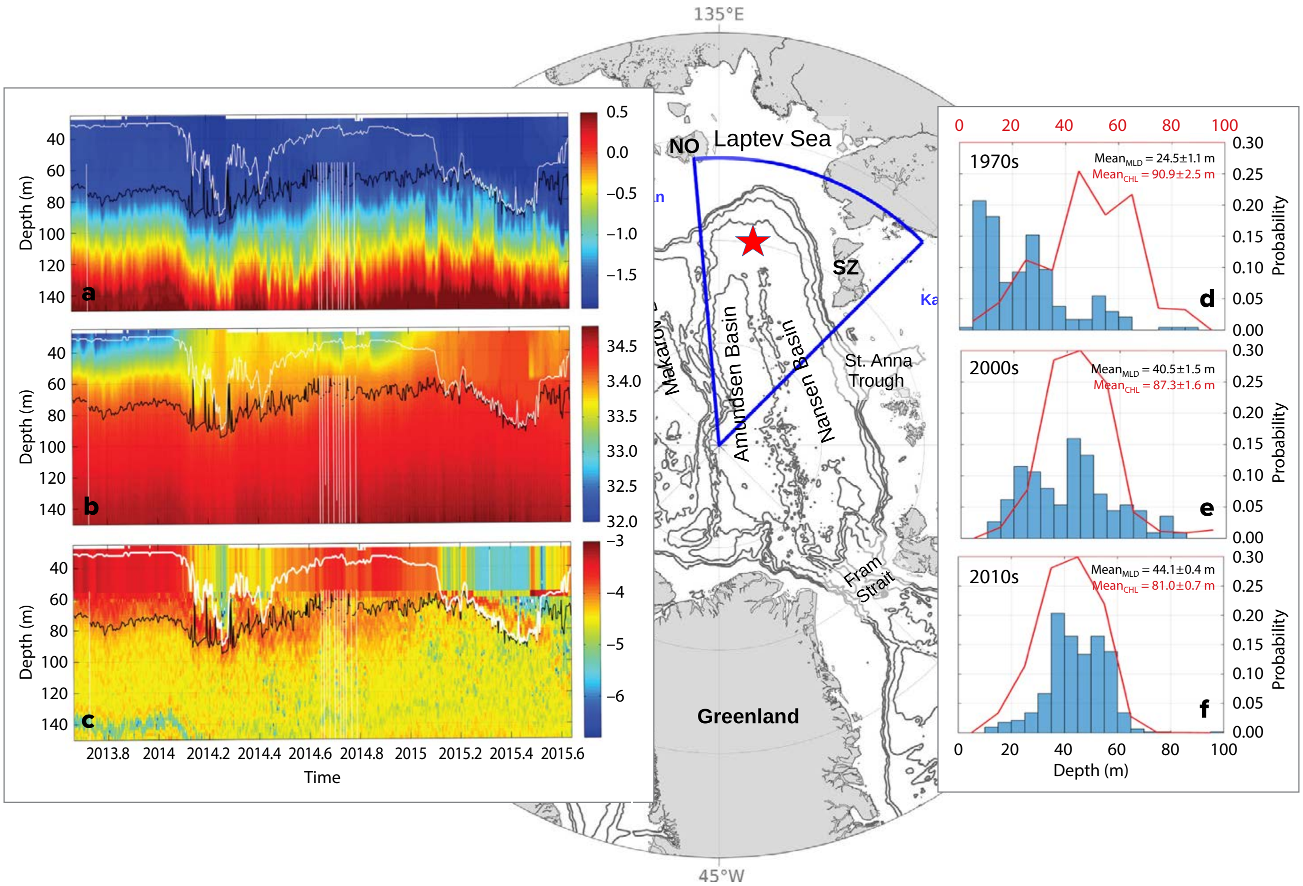

FIGURE 3. (left) Time vs depth diagrams of (a) potential temperature, (b) salinity, and (c) decimal logarithm of Brunt-Väisälä frequency in the eastern Arctic Ocean at mooring $M1_6$ (star on the background map within a blue triangle encompassing the Eastern Eurasian Basin). Mixed layer depth and cold halocline depth are shown by white and black lines, respectively. (map) NO indicates Novosibirskiye Islands and Severnaya Zemlya. (right) Probability distribution functions (PDFs) of the winter (February–April) surface mixed layer depth (MLD, blue bars) and the cold halocline layer (CHL, red line) lower boundary for the (d) 1970s, (e) 2000s, and (f) 2010s. Seven Russian annual surveys conducted from February to April provided CTD data for the 1970s, and the winter 2000s and 2010s CTD observations are mainly from Ice-Tethered Profilers (Toole and Krishfield, 2016). There is near doubling of the MLD in the 2010s compared to the 1970s, accompanied by ~10 m rise of the CHL boundary. Bimodal PDF structure is due to two winter convective regimes—shallow and deep. Both regimes shifted toward deeper MLD in the 2010s, suggesting that the "new" eastern Arctic Ocean is associated with deep penetrative ventilation of the upper ocean. The deepening of the MLD in the 2010s accompanied by the rise and weakening of stratification in the CHL suggest enhanced release of heat from the ocean interior to the upper ocean and to the bottom of the sea ice.

by a twofold amplification of currents in the semidiurnal band, which includes tides and wind-forced near-inertial oscillations. These results point to a new positive feedback mechanism in which increased winter ventilation of the ocean interior associated with declining sea ice cover and weakening of halocline stratification enhances release of heat from the ocean interior to the sea surface, resulting in further sea ice loss. This process is coincident with potential alteration of vertical nutrient fluxes that support oceanic primary productivity, food web structure, and carbon export from the deep ocean layers and seabed to the atmosphere (Polyakov et al., 2020a,b).

The rapid and unforeseen changes in the eastern Arctic climate system associated with Atlantification are complex, poorly understood, and require careful evaluation. Specifically, assessment of the potential for Atlantification in the EEB and its expansion further eastward into the Makarov Basin of the Arctic Ocean is critical for improving skills for seasonal sea ice predictions (Polyakov et al., 2021). A new (2021–2025) cycle of NABOS observations will enable us to quantify the role of freshwater inventories and transports in shaping upper ocean stratification and ventilation of AW heat in the vast area spanning eastward from Severnaya Zemlya to the central East Siberian Sea. New NABOS mooring design incorporates enhanced observational capabilities in the very top layer of the ocean and includes multidisciplinary oceanographic and sea ice sensors (Kipp and Charette, 2022, in this issue). One of the important results of the first 2021 cruise of this cycle was deployment of nine such moorings along the Siberian slope. These efforts will inform the scientific community and the broader public about major changes in the EEB and beyond, as well as their potential impacts for the state of ice cover, marine ecosystems, and conditions in the mid-latitudes.

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ARCTIC OCEAN BOUNDARY EXCHANGES

A REVIEW

By Sheldon Bacon, Alberto C. Naveira Garabato,
Yevgeny Aksenov, Nicola J. Brown, and Takamasa Tsubouchi

Moderate Resolution Imaging Spectroradiometer (MODIS) image of pack ice along the East Greenland coast that escaped the Arctic Ocean through Fram Strait, July 20, 2020. *Image credit: NASA Earth Observatory*

ABSTRACT. The Arctic Ocean has long been—and to a large extent remains—a data-sparse region. Paucity of ocean and atmosphere measurements impacts the fidelity of atmospheric reanalyses, and ungauged rivers lead to uncertainties in measurement-based estimates of river runoff. However, there exists a data resource that can provide material help: sustained (long-term) ice and ocean measurements around the Arctic Ocean boundary. The Arctic Ocean is surrounded by land and connects to adjacent ocean basins via four main gateways: to the Pacific through Bering Strait, to the Atlantic through Davis Strait, and to the Nordic Seas via Fram Strait and the Barents Sea Opening. In addition, the Nordic Seas connect to the Atlantic across the Greenland-Iceland-Scotland Ridge, which has a substantial measurement history. Inverse methods combine these data sets to generate conservative velocity fields that are then used to generate estimates of surface fluxes of heat and freshwater as well as other quantities of interest, including net biogeochemical fluxes and (with other methods) estimates of ocean water transformation rates. Data resources are available to greatly extend the duration and the temporal resolution of present analyses.

BACKGROUND

The primary motivations today for ocean monitoring are to determine the ocean's role in climate and climate change, and to quantify and understand ocean variability and trends in heat, freshwater, and carbon (and other biogeochemical) fluxes, as well as the impacts of such changes on other ecosystem-relevant parameters. We focus here on the Arctic Ocean, a relatively small body of water that is important for the global heat balance, and that is observed to be warming faster than the global mean rate as a consequence of regional feedbacks. We also include the Nordic Seas, a key buffer zone or transitional basin between the subpolar North Atlantic and the Arctic Ocean, where much of the regional dense water formation—via surface heat loss—occurs. The Arctic Ocean is unusual. It only comprises ~3% of the global ocean surface area, but it receives >10% of global river runoff; it is >50% (by area) relatively shallow shelf seas, the rest is deep ocean; and it is largely surrounded by land (Jakobsson, 2002; Carmack et al., 2016).

The regional geography—the confinement of the Arctic Ocean and Nordic Seas by land—is what makes ocean boundary monitoring feasible (Figure 1). The Arctic Ocean connects to adjacent basins through narrow and/or shallow gateways: to the Pacific through Bering Strait, to the subpolar North Atlantic through Davis Strait, and to the Nordic Seas through the Barents Sea Opening and Fram Strait. Of these four, only Fram Strait is deep. The Nordic Seas connect to the subpolar North Atlantic across the relatively wide and shallow Greenland-Iceland-Scotland (GIS) Ridge. We note also the existence of one other exit from the Arctic Ocean. Fury and Hecla Strait separates the Canadian mainland from Baffin Island and may support a net throughflow from the Arctic Ocean, through the Canadian Arctic Archipelago, then on into Foxe Basin (north of Hudson Bay), and ultimately into the Labrador Sea via Hudson Strait. However, as Tsubouchi et al. (2012) argue, any such throughflow will be small, and presently available measurements indicate its mean to be smaller than its uncertainty.

Arctic Ocean boundary measurements allow calculation of ocean exchanges with adjacent basins and also air-sea fluxes. A closed circuit of measurements (which may or may not include coastline) defines a volume, enabling the application of inverse methods, developed in the ocean context in the 1970s from earlier seismology applications (see Wunsch, 1996). Inverse methods generate allowable, self-consistent adjustments to current velocities (and other parameters) within uncertainties, to conform to constraints—at a minimum, mass and salt conservation—without which, unaccounted residuals mean that net surface fluxes (of heat and freshwater) cannot be meaningfully calculated. As current measurements became more widely available, their incorporation into inversions increased the usefulness of the approach by better initialization and narrowed uncertainty range. Calculation of property divergences within the defined volume is then facilitated by the mass-balanced boundary velocity field, as demonstrated by Bryan (1962) for ocean

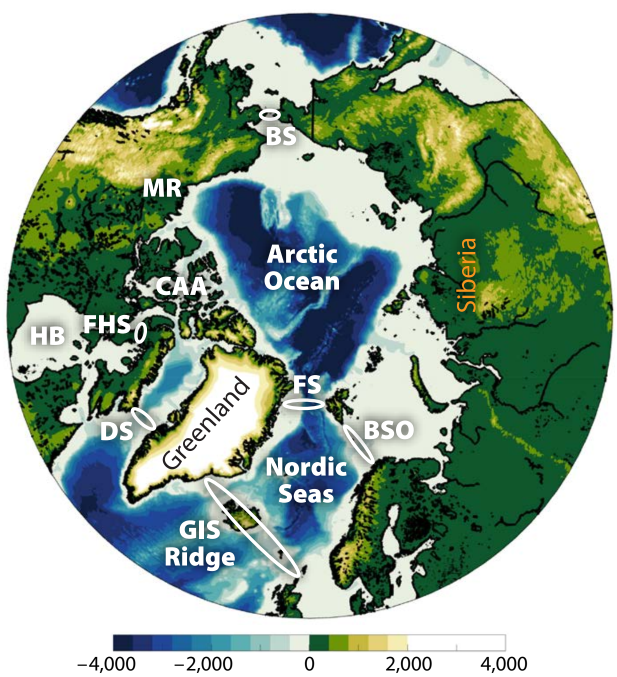

FIGURE 1. This regional map of the Arctic Ocean and Nordic Seas shows depths/elevations in meters (see scale). BS = Bering Strait. MR = MacKenzie River. CAA = Canadian Arctic Archipelago. FHS = Fury and Hecla Strait. HB = Hudson Bay. DS = Davis Strait. GIS = Greenland-Iceland-Scotland Ridge. BSO = Barents Sea Opening. FS = Fram Strait.

heat fluxes in a single-section context, and widely extended thereafter. The principle is straightforward: in the Arctic Ocean, mainly warm and saline seawater enters, and cooled and freshened seawater and sea ice leave. The amount of heat and freshwater required to effect these transformations is then the relevant surface fluxes.

The ability to calculate year-round property divergences within the Arctic Ocean from boundary measurements is useful because the Arctic is still data sparse, particularly for the deep ocean and the atmosphere and during winter–spring (November–May; see Behrendt et al., 2018). The regional lack of data is well illustrated by Cowtan and Way (2014, their Figure 1), who note that the different approaches taken to redress the deficiency all have limitations: extrapolation spreads out the (limited) available information, reanalyses essentially infill with dynamics, and remote-sensed (satellite microwave sounding) measurements are weighted to the lower troposphere and not the surface. While these resources are all valuable, ocean boundary measurements have the potential to provide independent, integral (regional) constraints on surface fluxes.

Data on heat exchanges between the atmosphere and the ice and upper ocean—derived from ocean boundary measurements—are now beginning to be used to better quantify and assess regional climate system parameters. Similarly, knowledge about total continental river runoff, which typically accounts for around one-third of the total runoff, is limited by the problem of ungauged rivers. There are several different approaches to addressing this limitation. Ocean surface freshwater fluxes derived from ocean boundary measurements are the sum total of evaporation, precipitation, and runoff, and may usefully constrain estimates of total runoff.

Net exchanges require simultaneous knowledge of all inflows and outflows, so here we confine ourselves to publications using mass-balanced ice and ocean velocity fields around the entire Arctic Ocean boundary, which are all derived using inverse methods. This review is structured as follows. The next section provides a brief overview of methods, focusing on recent developments. It is followed by sections describing computed surface heat and freshwater fluxes, physical oceanographic outcomes that examine water mass transformation rates, and the use of mass-balanced boundary velocity fields to compute net fluxes of biogeochemical quantities. We conclude with a summary and offer perspectives and comments relevant to this discussion.

METHODS

We do not further describe the application of inverse methods, which Wunsch (1996) thoroughly covers. Rather, we focus here on progress over the last 10 years in the calculation and interpretation of ocean (and sea ice) freshwater fluxes and heat fluxes.

Aagaard and Carmack (1989) first demonstrated the possibility of generating Arctic freshwater budgets and introduced "direct" and "indirect" methods. The former summed estimates of evaporation, precipitation, and runoff for a total of ~0.2 Sv (1 Sv = 10^6 m^3 s^{-1}), and the latter used ice and ocean budgets, ~0.1 Sv. The direct estimate proved to be quite robust, and improvements in ice and ocean measurements brought indirect estimates reasonably into line.

However, conventional calculation of ocean freshwater fluxes requires salinity "reference values," the choice of which has been plagued by arbitrariness, where authors typically justify their choices verbally, while a physically and mathematically consistent approach has been lacking. The ocean is ~96.5% freshwater, so how then to identify a particular fraction as somehow "different"? Development of a closed and complete method to quantify ocean freshwater fluxes was initiated in Tsubouchi et al. (2012) and extended by Bacon et al. (2015). This method begins with the observation that there is one location in the ocean where a true freshwater flux occurs unambiguously: the surface, where freshwater is exchanged with the atmosphere via precipitation and evaporation, and where the ocean receives freshwater from the land via river runoff, which is taken to include terrestrial glacial discharge. The outcome is an equation that expresses total surface freshwater flux, within an ocean volume enclosed by measurements (and coastline), as the sum of three terms: (1) the divergence of the salt flux around the ocean volume's boundary, (2) the change in total (ice and ocean) seawater mass within the ocean volume, and (3) the change in mass of salt within the ocean volume. Term (1) expresses the dilution of the (mainly saline) inflows by the surface freshwater flux to form the (freshened) outflows, and is also the steady-state solution, where seawater mass and its salt content are invariant. Terms (2) and (3) combine to isolate the net freshwater mass change in the full, time-varying solution. A scaling term emerges from the mathematics that resembles the traditional reference salinity, but it is the ocean volume's ice and ocean boundary-mean salinity. This may not, however, be the last word on the subject; for a critical review, see Solomon et al. (2021).

Bacon et al. (2015) apply the same approach to the (ice and ocean) surface heat flux as an exchange between ocean and atmosphere. It does not achieve a similarly closed form, because the transport by the (very small) boundary mean ocean velocity of the boundary mean temperature remains, which is unsatisfactory because it depends on the temperature scale.

Tsubouchi et al. (2012) provide an algebraic form and demonstrations of the impact on freshwater flux calculations of variant reference salinity choices. Within a closed circuit of measurements, the surface freshwater flux is only weakly sensitive (to ~1%–2%) to choice of reference salinity. However, when considering open hydrographic sections with a non-zero net mass budget, differences can be substantial—tens of mSv in volume terms, for changes of order 0.1 g kg^{-1} salinity. Furthermore, oceanographers wishing to calculate freshwater fluxes should consider not only how to do it but also what the computed flux means. As Carmack et al. (2016) illustrate, for the Arctic, the simplest case is that the surface freshwater flux dilutes all of the inflows to become all of the outflows. By considering the boundary gateways separately, the approach quantifies how the surface freshwater flux and the relatively fresh Bering Strait inflow combine to dilute (some of) the inflowing Atlantic-origin waters to become the outflows.

Budget approaches make no distinction between types of water molecules. However, evaporation and freezing act as distillation processes. Evaporation preferentially removes isotopically lighter (via oxygen) water molecules, which return in consequent precipitation and runoff. Freezing similarly produces isotopically lighter sea ice while rejecting heavier brine (high-salinity seawater with a higher proportion of the heavier isotopes). These characteristics are conservative and are distinctly separate in the phase space of salinity and the oxygen isotope (via its anomaly). Forryan et al. (2019) used a standard method to identify source fractions of seawater, meteoric freshwater, and sea ice/brine, which they then combined with boundary velocities to calculate transports. Within uncertainties, the oceanic meteoric freshwater flux (implicitly including runoff) was indistinguishable from the surface freshwater flux (as the total of precipitation minus evaporation plus runoff), reinforcing the robustness of both methods.

SURFACE HEAT AND FRESHWATER FLUXES

Tsubouchi et al. (2012) calculated the first quasi-synoptic estimates of pan-Arctic surface heat and freshwater fluxes. They assembled sea ice and hydrographic section data around the boundary of the Arctic Ocean from a 32-day period in summer 2005 and applied inverse methods to generate a mass- and salinity-balanced boundary velocity field. Their resulting net heat and freshwater fluxes were ~190 TW (from ocean to atmosphere) and ~190 mSv (into the ocean), respectively.

Tsubouchi et al. (2018) repeated the procedure, calculating a piecewise-continuous single annual cycle (from September 2005 to August 2006) of fluxes at monthly resolution, based synoptically on moored measurements. These first (almost) entirely measurement-based estimates of annual mean (±std) surface heat and freshwater fluxes are 175 ± 48 TW (15.5 ± 4.2 W m^{-2}) and 204 ± 85 mSv (6,400 ± 2,700 km^3 yr^{-1}), and the calculations include contributions of 22 ± 15 TW and 48 ± 32 mSv from sea ice. Their boundary heat flux variability through the year derives mainly from Atlantic water velocity variability and from surface water temperature variability, while the boundary freshwater flux variability is dominated by Bering Strait velocity variability. They inspect various published reanalyses, which give Arctic surface heat fluxes ranging from 5 W m^{-2} to 19 W m^{-2}, so that those at the lower end may appear questionable. They also note that their surface freshwater flux agrees with that of Haine et al. (2015), 6,770 km^3 yr^{-1}.

Tsubouchi et al. (2018) explain their neglect of storage as follows. Heat and freshwater storage are approximated as the sums of two components: repeating seasonal cycles of zero mean, and long-term trends (see Armitage et al., 2016). The annual averages of the ice and ocean boundary fluxes then accurately represent the annual averages of the surface fluxes, when the long-term trends are included as relatively small contributions to their uncertainties. They say "accurately represent" rather than "are equal to" because the ice and ocean boundary fluxes are the result of a complex convolution of the trajectories of individual water parcels with the action of surface fluxes upon them over many years, except at Fram Strait, where some of the northbound waters in the east of the strait may recirculate and only spend weeks to months inside the region before leaving southward in the west of the strait. Long residence times mean that seasonal heat and freshwater cycles (warming/cooling and melting/freezing) are local (i.e., largely confined within the boundary). Bacon et al. (2015) illustrate the consequent smoothing of surface fluxes using model output. The seasonal cycle amplitudes of surface and boundary heat fluxes are notably different, ~500 TW versus ~50 TW (or roughly 50 W m^{-2} and 5 W m^{-2}), respectively. The two freshwater seasonal cycles are more similar because some of the signal is a phase change with little net mass change.

Mayer et al. (2019) present the most cogent analysis of the Arctic climate system heat budget to date. A suite of largely independent observational and reanalysis products defines the atmosphere, sea ice, and ocean. They employ the same Arctic Ocean boundary measurement resources as Tsubouchi et al. (2018), but for four years (2005–2009), because they deem in situ-based oceanic transports to be more reliable than those from reanalyses. Budget closure is enforced per calendar month using a variational method. Focusing on their ice and ocean results, they find an annual mean surface heat flux of 16 W m^{-2} (ocean to atmosphere), with seasonal extrema in January (60 W m^{-2}, ocean to atmosphere) and July (94 W m^{-2}, atmosphere to ocean). They also estimate heat accumulation in the Arctic using a longer time base (2001–2017), indicating that the energy imbalance of the Arctic Ocean domain is ~1 W m^{-2}, with two-thirds going into seawater warming and one-third going into sea ice melting. Their analysis also identifies that, for the Arctic seasonal cycle, the largest source of uncertainty is sea ice thickness, because reanalyses only assimilate concentration. Furthermore, the ocean measurements show oceanic heat transports in ocean reanalyses to be too weak. Mayer et al. (2019) clearly demonstrate the value of measurement-based ocean flux estimates independent from other data products, as does the recent analysis of Arctic riverine discharges by Winkelbauer et al. (2022). Such estimates are used both to constrain choices of other data resources and are key to final quantified results. Mayer et al. (2019) note that ocean boundary measurements offer a "unique opportunity for long-term monitoring of the coupled Arctic energy budget."

Tsubouchi et al. (2021) extend the geographical range of northern high-latitude ocean heat flux estimation down to the region of the GIS Ridge. They employ a hybrid data set in which the main resources describing the Atlantic water inflows span the years 1993–2016 at monthly resolution. These critical measurements contain the bulk of the ocean heat transport variability. Some of the ocean transport records are shorter so, to obtain continuous monthly transport time series over the entire period, short time series were extended using the average value of the record modulated by its mean seasonal cycle. Inverse methods were applied to obtain closed budgets between the GIS Ridge, Davis Strait, and Bering Strait. They find that the mean ocean-to-atmosphere heat flux was 305 ± 26 TW, and that a statistically significant increase of 21 TW occurred within the period, after 2001. Using other published heat flux estimates (including Tsubouchi et al., 2018), they infer the heat flux over the Nordic Seas (excluding the Barents Sea) to have been 137 ± 34 TW.

INTERIOR MIXING AND NET VERTICAL EXCHANGES

The net water mass transformation exerted by the Arctic is to cool and freshen relatively warm, saline Atlantic-sourced waters that enter through eastern Fram Strait and the Barents Sea Opening and return southward east and west of Greenland via western Fram Strait and Davis Strait. Tsubouchi et al. (2018) calculate net (annual mean) freshening (by ~0.6 in salinity) and cooling (by ~3.7°C), for a density reduction of ~0.2 kg m^{-3}, not much different from the equivalent values for summertime from Tsubouchi et al. (2012). Some water returns denser than it entered, and some lighter, a twofold process that was first described as a double estuarine circulation by Carmack and Wassmann (2006). Brown (2019) quantifies this "two-cell" (double estuarine) vertical circulation in the Arctic Ocean in the first study derived from measurements.

To calculate density budgets for each isopycnal layer and thus infer the diapycnal mixing rates needed to maintain Arctic stratification, Brown (2019) uses the formulation of Walin (1982), adapted for density transformations by Large and Nurser (2001), whereby advective fluxes of density are taken to be balanced by density fluxes at the surface and by turbulent diffusion of density in the interior. The Tsubouchi et al. (2012) estimates of Arctic Ocean boundary velocities and density fields are used, with surface flux data from atmospheric reanalyses. Climatologies are employed to estimate total monthly river runoff and to define areas of surface flux integration.

The principal finding of Brown (2019) is that the inflowing Atlantic waters are indeed split, with portions transformed into both lighter and denser waters, confirming the existence of an overturning circulation with both an upper and a lower cell. Densification is due to surface heat loss and is concentrated in the southwestern part of the Barents Sea where warm Atlantic waters enter the region. In the lower cell, 1.8 Sv of inflowing Atlantic waters become more dense through surface heat loss; diapycnal mixing plays a secondary role here. Buoyancy gain, on the other hand, results from net freshwater input to the Siberian shelves and also offshore of the Mackenzie River outflow. In the upper cell, 1.0 Sv of Atlantic waters are transformed into lighter waters through mixing with surface-freshened water classes. These waters still lose heat to the atmosphere, but the upward flux of density is dominated by turbulence.

The density budget requires a positive upward diffusive density flux, equivalent to (pan-Arctic) diffusivities throughout the water column of ~1×10^{-5} m^2 s^{-1}, decreasing to ~1×10^{-6} m^2 s^{-1} toward the surface. Therefore, in contrast to some previous studies, Brown (2019) finds that in the Arctic Ocean, diffusive fluxes due to subsurface diapycnal mixing play as significant a role as surface buoyancy fluxes in controlling water mass transformations. Figure 2 illustrates the two-cell overturning results in density terms.

As first observed by Mauritzen (1996), water mass densification by surface heat loss in the Nordic Seas is largely responsible for the conversion of Atlantic

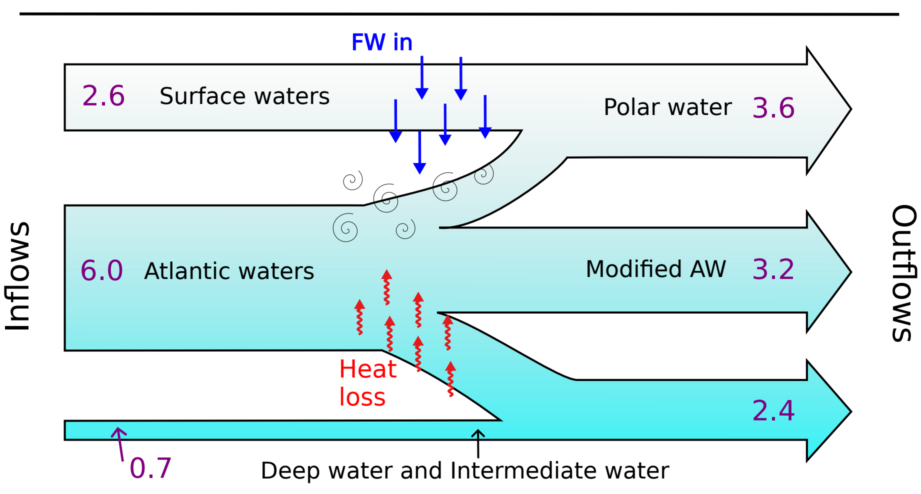

FIGURE 2. Schematic of the Arctic Ocean two-cell overturning in density space. Heat loss and freshwater (FW) input occur at the surface. Volume transports at entry and exit are shown in Sv. Interior diapycnal transports out of the Atlantic waters are 1.8 Sv dense waters downward and 1.0 Sv lighter waters upward.

waters into the dense, intermediate-depth water masses that overflow the GIS Ridge and descend to form headwaters of the Atlantic Meridional Overturning Circulation (AMOC; Frajka-Williams et al., 2019). Given a temperature difference of 8.4°C and an overflow volume transport of 5.5 ± 0.3 Sv, Tsubouchi et al. (2021) state a required heat loss of 189 ± 14 TW for this densification. Assuming that all of the heat loss is used to form the overflows, the 137 TW heat loss in the Nordic Seas can create 4.0 Sv of overflow waters, which also implies that the remainder of the densification, equivalent to 1.5 Sv, must happen in the Arctic Ocean (including the Barents Sea).

Overall (and approximately), therefore, 9 Sv of seawater enter the domain of the Nordic Seas and the Arctic Ocean, comprised of 1 Sv Pacific and 8 Sv Atlantic waters. One Sverdrup of the Atlantic water is transformed in the Arctic Ocean into lighter waters, to supplement the 1 Sv cold and fresh Pacific water, leading to 2 Sv exported in the upper cell. Four Sverdrups are made denser in the Nordic Seas and 1.5 Sv in the Arctic Ocean, to be exported in the lower cell as GIS Ridge overflow waters (see Isachsen et al., 2007). This leaves perhaps 1.5 Sv Atlantic water to be modified isopycnally, likely in the Nordic Seas, as illustrated by Strass et al. (1993), and exported in the boundary current system. Below 1,000 m depth in Fram Strait, there is near-zero (likely ~0.5 Sv southward) net deep transport.

BIOGEOCHEMICAL FLUXES

A group of papers used the mass-balanced boundary velocity field of Tsubouchi et al. (2012) to generate new baseline Arctic biogeochemical flux estimates for carbon and inorganic and organic nutrients (nitrate, phosphate, silicate). We summarize each of these here.

MacGilchrist et al. (2014) present observation-based estimates of dissolved inorganic carbon (DIC) fluxes using an assemblage of DIC data from the early 2000s. They calculated a net summertime pan-Arctic Ocean export of 231 ± 49 Tg C yr^{-1}, and estimate that at least 166 ± 60 Tg C yr^{-1} is due to ocean uptake of atmospheric CO_2, noting that time-dependent changes in carbon storage are not quantified. To advance understanding of the Arctic's role as a carbon sink, they calculated the net DIC transport beneath a prescribed mixed layer depth of 50 m, calling it the "interior transport," which revealed an export of 61 ± 23 Tg C yr^{-1}. They then inferred the sources of interior transport by using a "carbon framework," which implied that this export is primarily due to the sinking and remineralization of organic matter, highlighting the importance of the biological pump. They further showed qualitatively that beneath the mixed layer the present-day Arctic Ocean is accumulating anthropogenic carbon imported in Atlantic waters. Recent research by Terhaar et al. (2021) indicated that ~90 Tg C yr^{-1} are supplied to the Arctic Ocean by rivers and by coastal erosion, supporting about one-third of primary production; neither source is yet included in models.

Torres-Valdes et al. (2013) used near-synoptic nutrient data from summertime 2005 (as for the velocity field of Tsubouchi et al., 2012) to calculate net fluxes of dissolved inorganic nutrients: nitrate, phosphate, and silicate. They found net exports out of the Arctic (into the North Atlantic) of phosphate and silicate, while the nitrate budget was balanced (within uncertainty). Around the Arctic Ocean boundary, Fram Strait nutrient fluxes are in near balance, Bering Strait hosts the main import of silicate, and the Barents Sea Opening the main imports of nitrate and phosphate; the major exports of all nutrients to the North Atlantic occur via Davis Strait—also true of DIC. Exploration of possible sources of nutrients showed that rivers could supply most of the silicate imbalance, while the cause of the phosphate imbalance remained opaque. Nitrate presented another puzzle: known mechanisms that remove nitrate by denitrification had no obvious balancing source. They hypothesized that oceanic inputs of dissolved organic nutrients might account for the sources of nitrate and phosphate.

To test this latter hypothesis, Torres-Valdes et al. (2016) generated "indicative" budgets of organic nutrients by associating relevant nutrient concentrations from spatially and temporally limited measurements with major water masses, and then estimating net fluxes. To support the hypothesis, results should have yielded net imports equivalent to the denitrification rate and to the phosphate export—but they did not. While this negative result was inconclusive, they presented an agenda for future research that should explain the inorganic nitrate and phosphate discrepancies, which they grouped into three categories. First, noting that the inorganic nutrient data were collected between late spring and autumn, they ask whether seasonality may play a role via riverine nutrient supply, denitrification rates, or microbiologically mediated production of dissolved organic matter. Year-round nutrient measurements are beginning to emerge (e.g., Hennon et al., 2022, for Bering Strait). Second, noting the organic nutrient budgets to be indicative rather than strictly quantitative, they consider aspects of representativeness, particularly concerning the inference of Bering Strait concentrations from Beaufort Sea measurements; the low measurement resolution, which may not adequately represent features like the Fram Strait recirculation or the various narrow coastal currents; and the high degree of uncertainty in denitrification rates. Third, they note the existence of other possible nutrient sources. The atmospheric deposition rate is expected to be low, so it is an unlikely candidate; however, it has been suggested that the melting of the Greenland Ice Sheet may drive large nutrient supplies to the fjord systems around Greenland. The proportion of this source that might become bioavailable—and on what timescales—is yet to be determined. To this list can also be added shore runoff (distinct from river runoff) and coastal erosion (see Terhaar et al., 2021).

In addition to the "source fraction" results noted above, Forryan et al. (2019) presented another interesting result that employed inorganic nitrate and phosphate transports. The difference between Pacific and Atlantic nitrate-to-phosphate (N:P) ratios has been used by various authors as a water mass tracer. Forryan et al. (2019) find that water mass conversion does not preserve these nutrient characteristics, so that while the N:P ratios hold for source waters entering the Arctic, they become ambiguous (at best) on leaving, because denitrification (and possibly other processes) "convert" a fraction of the inflowing Atlantic waters to give them the appearance (in nutrient terms) of Pacific water. A further difficulty introduced by this use of the N:P ratio is degeneracy, where two supposedly independent conditions apply to the same water mass, an example of which concerns (again) Pacific water, which must both be 100% of Pacific origin and contain a significant fraction of meteoric water.

SUMMARY, COMMENTS, AND PERSPECTIVES

Summary

There is great value, of course, in sustained ice and ocean observing of the four individual Arctic boundary gateways separately, but we have not covered that aspect here. Rather, we have considered the significant utility of treating the four as an integrated boundary array, because, in combination, and with the use of inverse methods to enforce conservation constraints, they act as a basin-wide "instrument" that can provide measurement-based quantifications of net surface fluxes of heat and freshwater; in addition, they are independent of other resources (extrapolations, reanalyses, and satellites) that all involve making assumptions in order to address surface data sparsity. The resulting ice and ocean boundary velocity fields are further useful for examining water mass transformation rates within the boundary, and, when combined with measurements of biogeochemical parameters (carbon, inorganic and organic nutrients), have generated baseline quantifications of net ocean fluxes of these parameters, against which future assessments of past and future variability can be gauged. Next, we offer some observations on potential future progress.

Fury and Hecla Strait

Any net mean and variability estimates of seawater and freshwater export through this strait remain unclear. The main strait is wider than the local deformation radius, tides are strong, and the strait is seasonally ice covered. A complication is that the strait is largely—but not completely—blocked at its eastern end by a complex of small islands, of which Ormonde and Eider are the largest, so that mid-strait measurements thus far appear to be hard to translate to net throughflows at its eastern end. We think that the measurement challenge is, therefore, considerable. But the widest gap, between the Canadian mainland and Ormonde Island, spans only 2 km, while the others are much smaller. Measurements here to quantify any net throughflow would be valuable.

Fram Strait

Geographically, as the choke point between Greenland and Svalbard, Fram Strait is the inevitable choice for the location of sustained measurements. Geophysically, however, it was recognized from the start as difficult (e.g., see Fahrbach et al., 2001, and their struggle even to generate stable averages of key parameters). We illustrate these difficulties with Figure 3, which shows example model realizations of the winter maximum (mean January) surface heat flux with the barotropic stream function.

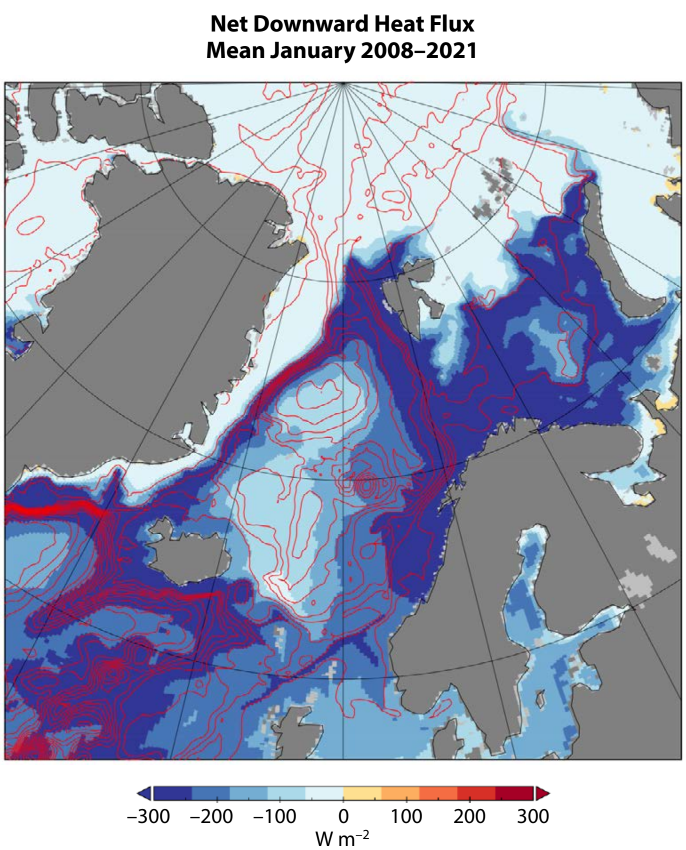

FIGURE 3. Net downward heat flux. Blues indicate ocean to atmosphere, and red contours show barotropic stream function (contour interval 4 Sv). January mean for 2008–2021 is from Nucleus for European Modelling of the Ocean (NEMO) 1/12° ice-ocean model with regional resolution of 3–5 km (Megann et al., 2021). Surface forcing is from JRA-55 (Tsujino et al., 2018, updated).

The measurement array is oriented zonally across 79°N, which runs through the middle of the maximum surface heat flux and is also parallel to the mid-strait flow (the local recirculation). Ambiguity remains even in the more recent interpretations of Tsubouchi et al. (2012, 2018) over assignment of local currents that run counter either to the boundary current systems or to mid-strait recirculation and thus affect the interpretation of the magnitude of those currents (but not of net flux calculations). **Figure 3** shows closed streamlines that recirculate around the margins of the whole of the Nordic Seas (as also modeled by Nøst and Isachsen, 2003). These streamlines also loop northward through Fram Strait and then back southward, leading to volume fluxes entering the Arctic Ocean that appear to be larger than the GIS Ridge inflows (and similarly for outflows), but which reflect (in part) circulation patterns internal to the Nordic Seas. Comparisons between measured results and models (forced ice-ocean, coupled climate) require care regarding consistency.

The AMOC

Concerted measurement of the AMOC began in 2004 with the RAPID array[1] of 19 moorings across the North Atlantic subpolar gyre, where the overturning circulation is readily defined in two parts—north-going warm and saline upper waters and south-going, colder, denser deep waters—and quantified on pressure surfaces (Frajka-Williams et al., 2019). However, this model is insufficient in the subpolar gyre because the AMOC possesses a third "leg" in the cold, fresh western boundary currents, and because the "flat" metric does not capture the water mass transformations that occur in the horizontal circulation. Instead, a "tilted" metric, based on density surfaces, is needed (Lozier et al. 2019). We can now clearly see the origin of this tripartite AMOC in the Arctic Ocean, with freshwater sourced in the subpolar boundary currents as well as in Nordic Seas heat loss and water mass modification. However, the apparent disappearance of the third leg between the subpolar and subtropical gyres presents a conundrum. Part of the answer is likely found in deep convection and deep winter mixing (in the Labrador, Irminger, and Iceland Seas) and in eddying, interior pathways (Bower et al., 2009) that inject waters into the deep, southward-flowing limb of the AMOC. But does vertical circulation at the front between the northern side of the North Atlantic Current and the interior of the gyre (e.g., Pollard and Regier, 1992), contribute to the change?

Long Surface Flux Time Series

The original expectation (or hope) driving the generation of Arctic net surface fluxes of heat and freshwater from ice and ocean measurements was based on their likely usefulness as independent resources in a data-sparse region, and we have shown that that expectation is being realized. Continuous measurement resources exist all around the Arctic Ocean boundary to extend the time series over two decades, from the early 2000s to the present, and it is to be hoped that this will happen sooner rather than later. As Mayer et al. (2019) point out, to resolve surface flux variability at sub-annual (monthly, seasonal) timescales requires knowledge of heat and freshwater storage and variability inside the boundary. Rabe et al. (2014) are beginning to be able to measure the interior seasonal cycle from in situ resources, and Armitage et al. (2016) show that wide-area remotely sensed measurements can detect mass and steric storage changes on monthly timescales. Perhaps a combination of the two can quantify the seasonal cycle.

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SIDEBAR > INCREASING FRESHWATER FLUXES FROM THE GREENLAND ICE SHEET OBSERVED FROM SPACE

By Bert Wouters and Ingo Sasgen

With a potential sea level contribution of 7.4 m (Morlighem et al., 2017), the Greenland Ice Sheet is by far the largest freshwater reservoir in the Northern Hemisphere. In addition to precipitation that nourishes the ice sheet throughout the year, summer above-freezing temperatures cause surface melt. Part of the meltwater refreezes in the snowpack, but a considerable part runs off to the ocean. The difference between precipitation and runoff is referred to as the surface mass balance (SMB). Typically, when averaged over a year, snowfall exceeds runoff, resulting in accumulation of mass on the ice sheet. This mass gain is counteracted by the slow but steady flow of glacier that transports ice toward the margins of the ice sheet and eventually to the ocean, where it either melts or calves as icebergs.

For an ice sheet to be in balance, the input (SMB) and output (ice discharge) terms need to equal each other. This balance held until the 1980s (Mouginot et al., 2019), when SMB gradually started to decrease. Regional climate models show that precipitation has remained about constant, but atmospheric warming has resulted in a dramatic increase in meltwater production. Comparing the period 1990–2015 against 1960–1989 shows an increase in melt volumes of more than 30%, with melt now exceeding precipitation in some years (van den Broeke, 2016). The second component of the mass balance equation—ice discharge—was relatively stable until the early 2000s, when widespread retreat and acceleration of the glaciers occurred, resulting in an approximately 14% increase in ice discharge (King et al., 2020).

Together, these shifts moved the ice sheet into a state of disequilibrium, reducing the volume and mass of the ice sheet, while at the same time adding to sea level rise. The associated redistribution of mass on Earth's surface can be observed by NASA's Gravity Recovery And Climate Experiment (GRACE; 2002–2017) and its successor GRACE-FollowOn (GRACE-FO; 2018–present). Both missions consist of two satellites following the same near-polar orbit but separated by about 220 km. Rather than measuring mass redistribution on Earth's surface directly, GRACE measures local changes in Earth's gravitational field due to this redistribution. Because the gravitational force acting on the satellites is inversely proportional to the square of the distance to the attracting mass (see Newton's Law), the impact of a local mass redistribution on the orbit of the leading satellite will be different from that of the trailing satellite. This results in constant changes in the intersatellite distance on the order of microns, which are continuously measured using a ranging system onboard the satellites. From this, monthly estimates of anomalies in Earth's geoid are estimated, which in turn can be converted to surface mass loading anomalies (Wahr et al., 1998; Tapley et al., 2019).

Figure 1a shows the observed mass change integrated over the Greenland Ice Sheet. On average, the ice sheet lost 268 ± 20 gigatons per year between 2002 and 2021, but the annual mass loss varies substantially. Exceptionally

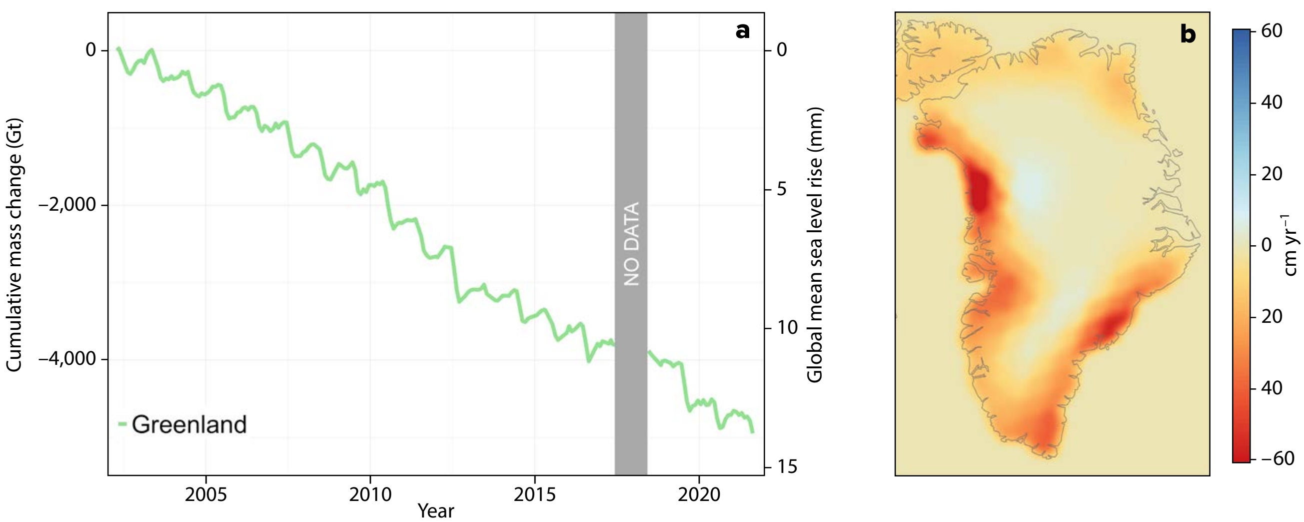

FIGURE 1. (a) Mass changes observed by NASA's Gravity Recovery And Climate Experiment (GRACE; 2002–2017) and its successor GRACE-FollowOn (2018–present) integrated over Greenland. (b) Spatial pattern of linear trends (2002–2021) in equivalent water height (EWH) per year. As a reference, 1 mm EWH corresponds to a surface loading of 1 kg m^{-2}.

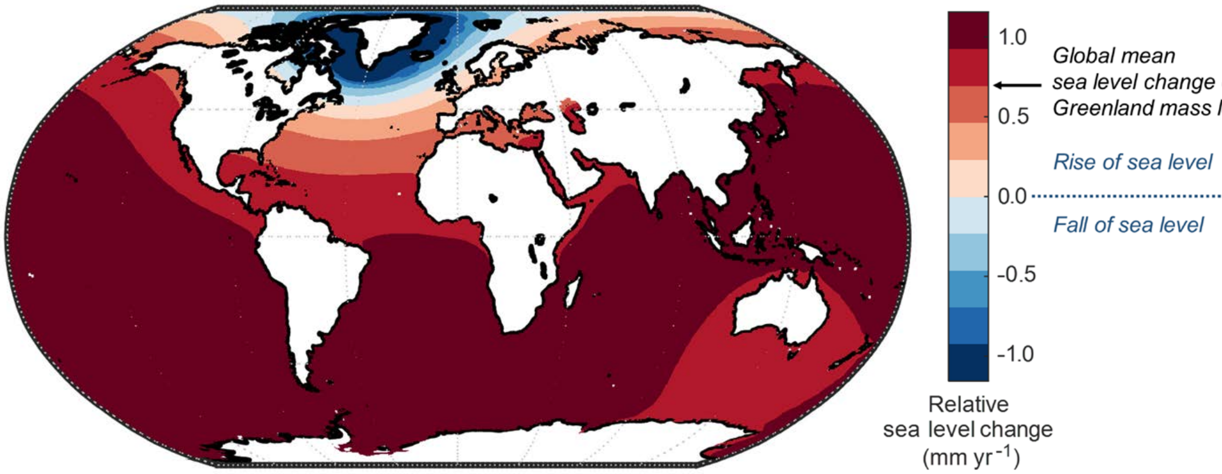

FIGURE 2. Relative sea level change induced by the mass changes in Figure 1b.

large losses on the order of 500 gigatons in a single year were recorded by the GRACE/GRACE-FO missions in 2012 and 2019. In these years, primarily anticyclonic atmospheric circulation patterns advected warm air from mid-latitudes toward the ice sheet, leading to surface melt up to the highest altitudes of the ice sheet. Conversely, in 2017 and 2018, low-pressure systems residing over the ice sheet transported cold Arctic air southward, causing anomalously low summer temperatures and surface melt (Sasgen et al., 2020). Together with above-average snowfall during winter, this resulted in SMB values otherwise unmatched in the GRACE/GRACE-FO era. In the decades preceding the 2000s, such conditions would have led to ice sheet growth. Yet, the GRACE/GRACE-FO satellites recorded a net mass loss due to the elevated level of ice export through glacier flow.

In the 20-year record, the Greenland Ice Sheet contributed 14 mm to global mean sea level rise. However, the total freshwater input to the ocean is larger because of the precipitation feeding the ice sheet. With an estimated mean annual total precipitation of 906 gigatons per year for the same period (Noël et al., 2018), the Greenland freshwater flux sums to 1,174 km^3 per year, equivalent to 0.04 Sverdrup (1 Sv = 1×10^6 m^3 s^{-1}). To put this flux in perspective, it corresponds to about 30% of the observed pan-Arctic river discharge (4,025 km^3 yr^{-1} between 1981 and 2019; Winkelbauer et al., 2022), or 45% of the annual liquid freshwater flux through the Bering Strait (2,500 ± 100 km^3 yr^{-1} for 2000–2010; Haine et al., 2015). As Figure 1b shows, the mass loss is not uniformly distributed but rather is concentrated along the margins of the ice sheet in the northwest, where glaciers have sped up dramatically since the 2000s (Mouginot et al., 2019; King et al., 2020), and the southeast, where an increase in ice discharge and meltwater runoff contribute about equally (Mouginot et al., 2019). Consequently, freshwater influx has mainly increased in the North Atlantic, Davis Strait, and Baffin Bay, where the accumulated freshwater may affect biological productivity and ocean circulation (e.g., Bamber et al., 2018).

When considering the impact on sea level, it should be kept in mind that the mass loss of the Greenland Ice Sheet induces a distinct pattern of relative sea level change over the global ocean. Mass loss in Greenland reduces the gravitational attraction in the ice sheet's vicinity but causes a slight increase over the global ocean. Consequently, less ocean water is pulled toward the ice sheet, causing a local fall of sea level in its vicinity and a rise in its far field. Additionally, the redistribution of mass loading leads to instantaneous elastic deformation of Earth's surface, causing uplift in the region of mass loss, further increasing the fall of the sea level relative to the land. Finally, the mass redistribution changes Earth's inertia tensor, resulting in rotational variation and an associated long-wavelength sea level pattern. The self-consistent treatment of these three effects is described in a linear integral equation called the "sea level equation" (Woodward, 1888; Clark et al., 1978; Spada and Stocchi, 2006). Figure 2 shows the resulting pattern of relative sea level change induced by the mass changes observed by GRACE/GRACE-FO. Typically, ice loss in polar regions leads to a disproportionate sea level rise in the mid-latitudes (Mitrovica, 2009; Kopp et al., 2015; Jevrejeva et al., 2016), which needs to be taken into account in projections and historical reconstructions of sea level.

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AN INTERDISCIPLINARY PERSPECTIVE ON

GREENLAND'S CHANGING COASTAL MARGINS

By Fiammetta Straneo, Donald A. Slater, Caroline Bouchard, Mattias R. Cape, Mark Carey, Lorenzo Ciannelli, James Holte, Patricia Matrai, Kristin Laidre, Christopher Little, Lorenz Meire, Helene Seroussi, and Maria Vernet

Sermilik Fjord, in the Ammassalik region of Southeast Greenland, is characterized by an increasingly dense iceberg pack (the ice melange) from the discharge of several large glaciers at its head. Scientists aboard M/V *Adolf Jensen*, including several of the coauthors, collect oceanographic data to inform understanding of fjord circulation and nutrient cycling through these systems. *Photo credit: Jamie Holte, Scripps Institution of Oceanography, UCSD, August 2021*

ABSTRACT. Greenland's coastal margins are influenced by the confluence of Arctic and Atlantic waters, sea ice, icebergs, and meltwater from the ice sheet. Hundreds of spectacular glacial fjords cut through the coastline and support thriving marine ecosystems and, in some places, adjacent Greenlandic communities. Rising air and ocean temperatures, as well as glacier and sea-ice retreat, are impacting the conditions that support these systems. Projecting how these regions and their communities will evolve requires understanding both the large-scale climate variability and the regional-scale web of physical, biological, and social interactions. Here, we describe pan-Greenland physical, biological, and social settings and show how they are shaped by the ocean, the atmosphere, and the ice sheet. Next, we focus on two communities, Qaanaaq in Northwest Greenland, exposed to Arctic variability, and Ammassalik in Southeast Greenland, exposed to Atlantic variability. We show that while their climates today are similar to those of the warm 1930s–1940s, temperatures are projected to soon exceed those of the last 100 years at both locations. Existing biological records, including fisheries, provide some insight on ecosystem variability, but they are too short to discern robust patterns. To determine how these systems will evolve in the future requires an improved understanding of the linkages and external factors shaping the ecosystem and community response. This interdisciplinary study exemplifies a first step in a systems approach to investigating the evolution of Greenland's coastal margins.

INTRODUCTION

The coastal margins of Kalaallit Nunaat (Greenland) are unique regions shaped by the confluence of Atlantic and Arctic Ocean waters; the discharge of icebergs, meltwater, and sediments from the ice sheet; the formation, melt, and transit of sea ice; and the battering of extreme storms and katabatic winds. They comprise shallow continental shelves incised by deep troughs scoured by ice streams during glacial periods, and hundreds of glacial fjords, some over a kilometer deep, tens of kilometers long, and only a few kilometers wide. The interaction of ocean currents, glaciers, and winds gives rise to nutrient-rich waters and other conditions that support rich marine ecosystems, including a high density of seabirds, marine mammals, and fish (Figure 1). These coastal ecosystems, in turn, support people and communities whose sustenance, livelihoods, and culture have adapted to these dynamic conditions and have simultaneously shaped the fjord systems themselves. Understanding Greenland's coastal margins and its ecological and human systems ("social-ecological system," hereafter) therefore requires a "system description" that encompasses the many interacting components responsible for the conditions that presently sustain life.

Climate change, and the associated pronounced warming of the Arctic (Serreze et al., 2009), is driving rapid change in these regions as manifested by the retreat of glaciers, an increase in surface melt of land-ice, a shortened sea-ice season, rising air temperatures, and a meridional migration of species. Anthropogenically driven change adds to large-scale climatic fluctuations, including those associated with modes of climate variability that naturally characterize this region, such as the Arctic and North Atlantic Oscillations (Hurrell, 1995) and the Atlantic Multidecadal Oscillation (Zhang et al., 2019). Greenland's resilient human communities have historically adapted to these changes by shifting their hunting and fishing practices (Hastrup, 2018; Nuttall, 2020). However,

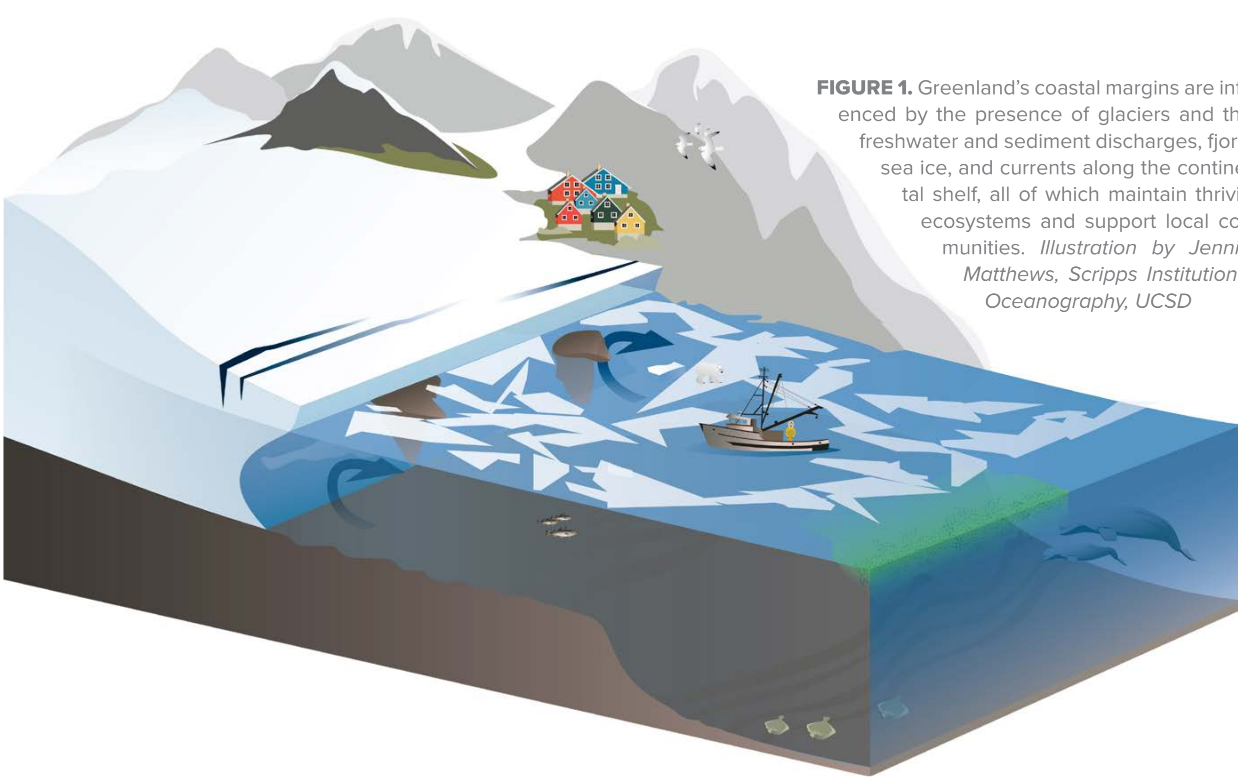

FIGURE 1. Greenland's coastal margins are influenced by the presence of glaciers and their freshwater and sediment discharges, fjords, sea ice, and currents along the continental shelf, all of which maintain thriving ecosystems and support local communities. *Illustration by Jennifer Matthews, Scripps Institution of Oceanography, UCSD*

climate projections indicate that future climate variability will exceed what has been observed over the last century and, eventually, what is recorded in the collective, historical memory of the inhabitants. Identifying when this will occur and understanding how this region will evolve in the future will help inform adaptive strategies for local residents.

In this review, we use data and models to identify the system of environmental conditions around Greenland that relate to indicators of the health of the marine ecosystem, the inshore and offshore fisheries, and the human settlements. One goal is to identify the overarching characteristics that support the thriving coastal environments around Greenland by considering the geographic and climatic forces that shape these environments. Next, we investigate the variability of several system components for two different regions, one in the Atlantic sector and one in the Arctic sector, to determine how variability over the last century might inform changes projected over the next century. The Qaanaaq region of Northwest Greenland and the Ammassalik region of Southeast Greenland are chosen as representative of a range of geographic, climatic, historical, and social settings across Greenland. Historical data and model reconstructions, in particular, are used to identify periods when the climate was similar to that of today and to determine when future projections will emerge beyond historical experience. A follow-up study will further explore the human dimensions of this system to analyze how climate and other biophysical forces intersect over time with political, economic, technological, and cultural forces.

CLIMATE, ECOSYSTEMS, FISHERIES, AND HUMANS AT GREENLAND'S COASTAL MARGINS – PAN GREENLAND

Kalaallit Nunaat (Greenland) stretches from the high Arctic (83°N) to the subpolar North Atlantic (59°N; Figure 2). The ~2 km thick Greenland ice sheet covers 81% of its area, confining its 56,000 inhabitants to a thin, ice-free coastal strip along the western and southeastern coasts. About one-third of Greenlanders live in Nuuk, the capital, while the remainder live in communities whose average population is 2,000 (Figure 2f). Greenland's coastal margins can be partitioned into four different oceanic sectors—the Arctic Ocean, the Nordic Seas, the North Atlantic subpolar gyre, and Baffin Bay—each dominated by different combinations of waters from the Arctic and Atlantic Oceans. Warm, salty Atlantic waters of subtropical origin flow along the eastern and western continental slopes, progressively encroaching onto the shelves through glacially carved canyons (Figure 2c,d). North of Denmark Strait, the Atlantic waters are subsurface and colder as a result of their transformation in the Nordic Seas. Inshore, along the entire eastern coast, the shelf is primarily occupied by cold, fresh water of Arctic origin that is associated with the export of water and sea ice from the Arctic Ocean through Fram Strait (Figure 2c; Kwok et al., 2004; de Steur et al., 2009). Here, sea ice extends south of 60°N, despite the presence of warm waters offshore (Figure 2e). This sea ice, and the associated colder coastal climate, is one of the main reasons that most of Greenland's inhabitants live on the west coast (Figure 2f), where the influence of the Arctic waters is diminished, and comparatively warm waters fill the continental shelves. Further north, in Baffin Bay, Greenland's coast is again influenced by Arctic waters, this time flowing south through Nares Strait (Figure 2c). North Greenland borders a cold, mostly sea ice-covered region of the Arctic Ocean characterized by ice ridging and quasi-permanent ice cover. These different water masses affect local air temperatures that are otherwise mostly uniform over much of the island. In particular, during winter, warm, Atlantic waters make the southeast coast warmer than the northwest coast (Figure 2a,b).

Environmental and geographic conditions along Greenland's margins result in strong spatial gradients in the timing of seasonal phytoplankton blooms and overall rates of primary production (Figure 2e). In general, Greenland shelf waters are medium to low in annual net community production (11–34 Tg C yr^{-1}) relative to other Arctic regions but tend to have higher net integrated primary production when subsurface and under-ice productivity are included in remotely sensed estimates (118 Tg C yr^{-1}; Codispoti et al., 2013; Hill et al., 2013). North-south differences in day length, sea-ice extent, air temperature, and water masses contribute to overall higher rates of production in the south compared to the north (Vernet et al., 2021), with blooms initiated earlier in the south (April versus June), resulting in longer productive seasons. These rates are on par with other productive high-latitude regions (Codispoti et al., 2013; Vernet et al., 2019). In areas that are strongly impacted by the presence of sea ice, including the north and east Greenland coasts (Figure 2e), spatial and temporal variability in primary production is mediated by the timing and mechanism of sea-ice retreat, with blooms typically initiated offshore along the sea-ice margin or under the ice and propagating shoreward (Mayot et al., 2018; Vernet et al., 2021).

Along the sea ice-dominated continental shelves of Northeast and Northwest Greenland, primary production is dominated by two polynyas (annually recurring areas of persistent open water bounded by the coast and pack ice offshore), the Pikialasorsuaq (North Water Polynya) and the Northeast Water Polynya (Tremblay and Smith, 2007; Marchese et al., 2017). The physical processes driving the early seasonal formations and sustained openings of these systems, including wind-driven advection of sea ice offshore, topographic steering and blocking of multi-year ice, and ocean-driven melting of sea ice by Atlantic-sourced waters, also contribute to high supplies of nutrients, allowing for unusually early, prolonged, and productive phytoplankton blooms that support rich marine ecosystems. Fluctuations in the extent of the

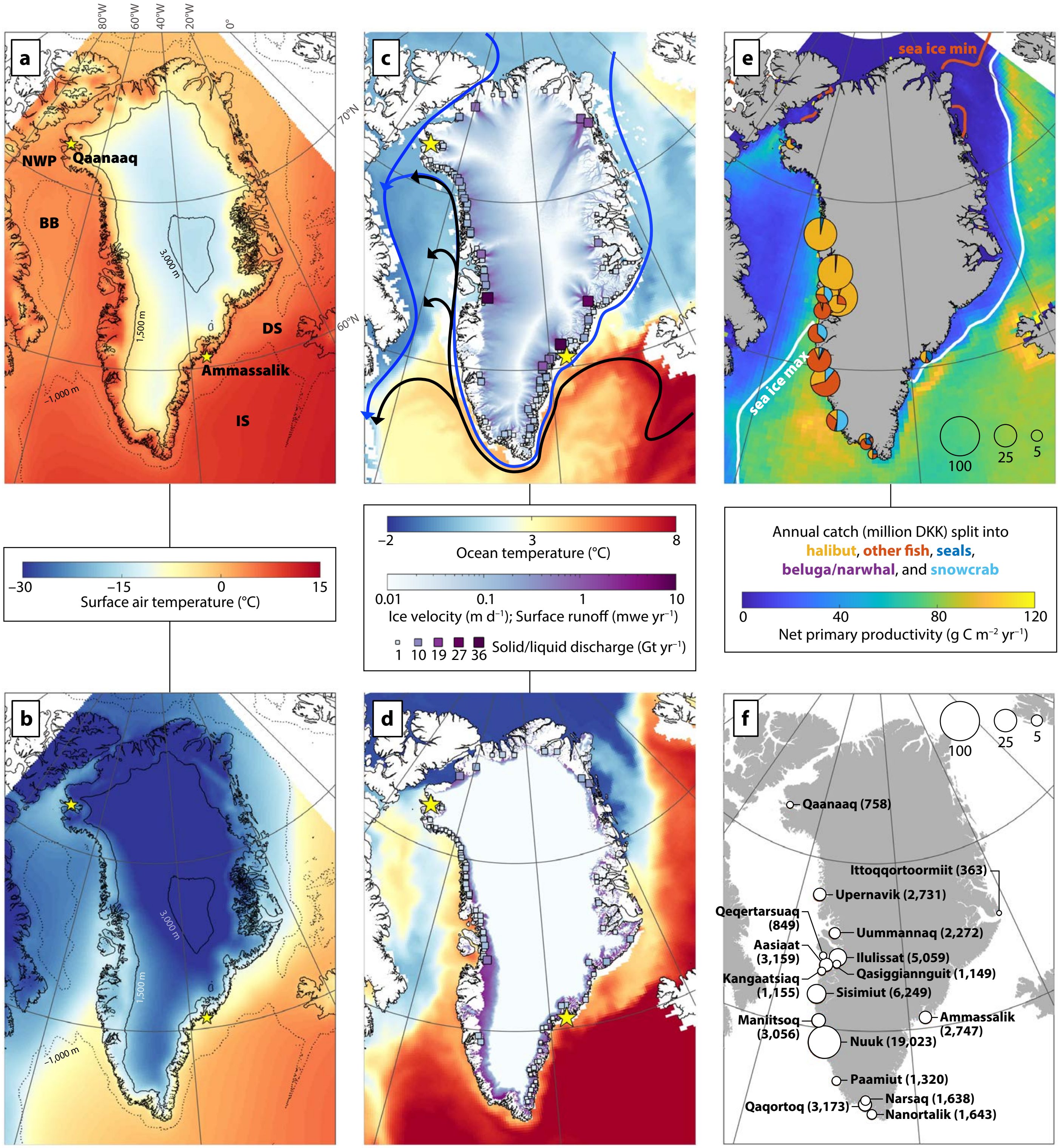

FIGURE 2. Present-day state of aspects of Greenland's climate, marine ecosystems, and communities. (a) Mean August surface air temperature from ERA5 (Hersbach et al., 2019). DS = Denmark Strait. IS = Irminger Sea. BB = Baffin Bay. NWP = North Water Polynya. (b) Mean February air temperature. (c) Mean August ocean temperature at 200 m depth from the Ocean Reanalysis System 5 (ORAS5; Zuo et al., 2019), ice flow velocity (filled contours; ESA CCI, 2021; mwe = meltwater equivalent), and solid ice discharge from major marine-terminating glaciers (squares, legend below; Mankoff et al., 2019). Arrows show mean currents transporting warm, salty Atlantic water (black) and fresh, cold Arctic water (blue). (d) Mean August surface ocean temperature from ORAS5, mean August surface runoff (filled contours), and the resulting liquid freshwater discharge from marine-terminating glaciers once integrated over their catchments (squares, legend above) from the Regional Atmosphere Climate Model (RACMO; Noël et al., 2018). (e) Annual mean net primary productivity modeled from remote sensing ocean color (Vernet et al., 2021) and annual catch of fish and marine mammals (Statistics Greenland, 2020). (f) Greenland's primary population centers (inhabitants in 2021; Statistics Greenland, 2020). Panels a, b, and e represent averages over 2003–2018, except for fisheries and marine mammal data, which are averages over 2012–2020. Data in panels c and d are 2018 only, while panel f shows 2021 data.

North Water Polynya, as recorded by the sediment record (Ribeiro et al., 2021), have coincided with major transitions in human occupation of the region, providing evidence for the long-term importance of this polynya to the human-natural coupled system (Speer et al., 2017).

Hundreds of glacial fjords, many containing large, fast-flowing marine-terminating outlet glaciers grounded hundreds of meters below sea level, connect the ocean with the ice sheet. Freshwater from glaciers released into the fjords in the form of icebergs (**Figure 2c**; Mankoff et al., 2019), meltwater from submarine melting of the ice front (Slater et al., 2019), runoff of surface melt (**Figure 2d**; e.g., Noël et al., 2016), and basal meltwater (Karlsson et al., 2021) is transformed by processes within the glacial fjords before being exported into the upper layers of continental shelf waters (Beaird et al., 2015, 2018; Moon et al., 2017). Deep troughs that cut across the continental shelf provide a pathway for warm, salty, denser shelf waters to flow into the fjords and drive melting of the glaciers at depth (Jakobsson et al., 2012; Straneo et al., 2012; Snow et al., 2021).

Seasonal surface runoff from the ice sheet's coastal margins (**Figure 2d**), discharged at the bases of large glaciers below the ocean surface, triggers rising plumes along the glaciers' faces, driving mixing and upwelling of deep, nutrient-rich ocean waters (Jenkins, 2011; Slater et al., 2015; Hopwood et al., 2018; Kanna et al., 2018; Cape et al., 2019). High rates of summertime primary productivity and phytoplankton biomass in fjords, coincident with nutrient enrichment of the upper water column downstream of marine-terminating glaciers, have been attributed to this process (Meire et al., 2017). This upwelling of nutrients is also thought to contribute to a lengthening of the growth season within the fjords, with secondary summer blooms accounting for an unusually large fraction of annual primary production (Juul-Pedersen et al., 2015).

Water is continuously exchanged between the fjords and the shelf regions as a result of offshore and katabatic winds, glacial transformation of ocean waters, and other mechanisms (Motyka et al., 2003; Jackson et al., 2014; Moffat, 2014; Carroll et al., 2017; Spall et al., 2017; Fraser and Inall, 2018). Sills and topography mediate this exchange (Mortensen et al. 2014). As a result, marine ecosystems within the fjord and over the continental shelf are not independent. For example, fjord-shelf exchanges have important consequences for the dispersal and retention of planktonic organisms, including larval fish, with consequences for the carrying capacity, recruitment, and genetic exchange among fish populations (Asplin et al., 1999).

The mixing of different water types and the consequent nutrient upwelling renders the shelf and fjord regions productive (Vernet et al., 2021). When the winter sea ice retreats, it triggers large primary production blooms on the shelf that attract high densities of zooplankton and lower trophic level forage fish (Laidre et al., 2008). Boreal forage fish, such as capelin and sand lance, are key species in the food webs of subarctic waters, while Arctic cod play this role in Arctic waters. These fish and zooplankton ultimately attract large numbers of marine mammals and seabirds. Additionally, glacial ice (in the form of the iceberg melange found at the margins of marine-terminating glaciers) provides a year-round habitat that can support Arctic species such as polar bears (Laidre et al., 2022). These unique environmental conditions around Greenland mean that it can host a species assemblage of year-round, true Arctic specialists (polar bears, narwhals, ringed and bearded seals) as well as large numbers of temperate marine mammal species (e.g., subarctic baleen whales, and a suite of dolphins and toothed whales) that migrate to the productive shelf waters during summer.

These rich marine ecosystems also support fisheries (**Figure 2e**) that are an important economic resource for Greenland, accounting for one-third of its annual revenue and constituting the largest employer after the public sector (Statistics Greenland, 2020). The 200-mile (320 km) fishing territory is composed of two managed fisheries: offshore and coastal (or "inshore," within 3 nautical miles). The coastal fleet includes more than 1,700 small boats, often owned by

The town of Tiilerilaaq (formerly Tiniteqilaaq) is a small settlement located in the middle of Sermilik Fjord in the Ammassalik district. Its community relies largely on hunting and fishing for sustenance. *Photo credit: Jamie Holte, Scripps Institution of Oceanography, UCSD, August 2021* individuals, that fish for Greenland halibut, Atlantic cod, snow crab, and lumpfish (Figure 2e). The offshore fleet consists of large fishing vessels owned by corporations that primarily trawl for shrimp and halibut (data not shown). Catches of Greenland halibut, both inshore and offshore, dominate in West Greenland, while catches of cod dominate in East Greenland, especially in areas of Atlantic water influence. While most of the inhabited areas, and all of the fishing processing plants, continue to be in West Greenland, in recent years East Greenland offshore fisheries have yielded most of the annual landings of cod and pelagic species. In addition to fisheries, marine mammal and seabird harvests are important activities.

HISTORICAL AND PROJECTED CHANGES IN AMMASSALIK AND QAANAAQ

The large spatial variability in climatic conditions around Greenland's margins, resulting from factors such as proximity to the Arctic or North Atlantic Oceans, the presence of sea ice, freshwater discharge from the ice sheet, glacial discharge, orography, and bathymetry, gives rise to localized areas of high marine productivity (Figure 2e). Human settlements in Greenland are typically located close to a subset of these productive regions where conditions are favorable for hunting, fishing, and human survival. Thus, any analysis of the variability affecting these social-ecological systems must be carried out at a regional scale. Here, we focus on two localities whose characteristics are at different ends of the range of systems in Greenland: Ammassalik in Southeast Greenland and Qaanaaq in Northwest Greenland.

Ammassalik ("the place with the capelin," located on Figure 2a) comprises six settlements and is one of only two inhabited regions in East Greenland. The largest settlement, Tasiilaq, has 2,000 inhabitants, while the others collectively have fewer than 250. Subjective well-being in this region is influenced by a range of factors, from social and family connections to employment, contact with nature, emotional state, health, education, and other factors that shape social life in East Greenland. In many cases, hunting, fishing, and the collection of local food (e.g., seal, trout, salmon) in and around the fjord system is vital to social well-being and quality of life here (Steenholdt, 2021). Along the coast, warm, salty waters from the Irminger Sea mix with cold, fresh waters from the East Greenland Current and the Coastal Current (Sutherland et al., 2013; Snow et al., 2021) to support high productivity on the continental shelf. In addition, upwelling of nutrient-rich waters from the many tidewater glacial fjords in the region results in an upward nutrient flux that replenishes depleted macronutrients in the upper part of the water column (Cape et al., 2019). These processes sustain a rich and diverse ecosystem that supports fisheries for the Ammassalik communities. Commercial fishing is more limited here than in West Greenland but has nonetheless helped produce economic opportunities, jobs, and infrastructure, such as transportation (Buijs, 2010; Moral García, 2019).

Qaanaaq, with approximately 650 inhabitants, is the largest of three settlements located along Inglefield Fjord in Northwest Greenland (Figure 2a for location). It was established in 1953, when the population from nearby Dundas/Pituffik was forcefully relocated so that the US military could build Thule Air Force Base (Flora et al., 2018; Hastrup, 2019). Inglefield is a wide, deep Arctic fjord where Kangerluarsuup (Bowdoin), Qeqertaarsuusarsuup (Tracy), Qaqujaarsuup (Helprin), and several other smaller glaciers terminate and help create nutrient rich, highly productive waters. Because a series of sills in the northern portion of Baffin Bay partially obstruct the transport of warm Atlantic Water by the West Greenland Current, subsurface waters in Inglefield Fjord are a relatively cold mixture of Arctic and Atlantic Ocean waters (Münchow et al., 2011; Willis et al., 2018). Thus, Inglefield Fjord is expected to be more strongly exposed to Arctic-sourced variability than Ammassalik. The ecosystem is also influenced by the Pikialasorsuaq (the "North Water Polynya"), a large, highly productive polynya in the northern part of Baffin Bay. Qaanaaq's community has long relied on subsistence hunting for seabirds and marine mammals, including

narwhal hunts from kayaks and polar bear hunts from dog sledge trips over the sea ice. Development of a Greenland halibut fishery over the last 10 years within Inglefield Fjord has accompanied other changes in hunting, fishing, and economic opportunities in this coastal region. These activities change not only with sea-ice loss and the shifting ocean-ice interface but also with a rise in tourism and international research that offer cash-based economic opportunities beyond subsistence (Flora et al., 2018).

Past and Projected Changes in Physical Climate

Historical physical climate data and model reconstructions indicate that Ammassalik and Qaanaaq have exhibited substantial variability in the atmosphere, the ocean, sea ice, and glaciers over the last 120 years (Figure 3), consistent with studies addressing variability on larger scales (e.g., Zweng and Münchow, 2006; Box et al., 2009; Straneo and Heimbach, 2013; Onarheim et al., 2018; Mouginot et al., 2019; Hanna et al., 2021). Collectively, these studies suggest that year-to-year variations in ocean and atmospheric variables over and around Greenland are linked with the North Atlantic and/or Arctic Oscillations (together denoted as NAO; Simpkins, 2021). A negative NAO is associated with a southward shift of the Atlantic storm track, reduced wind stress and wind-stress curl over the subpolar North Atlantic, and a warmer ocean in this region (Häkkinen et al., 2011). Thus, in coastal Greenland, a negative NAO is associated with a rise in coastal air temperatures (especially in West Greenland) and an increase in surface melt (and vice versa for a positive NAO). However, the details vary with each season, and the correlations are strongest in the earliest twentieth century and over the last few decades (Hanna et al., 2013). These same studies suggest that the multi-decadal variations around Greenland (Figure 3) are linked with the Atlantic Multidecadal Oscillation (AMO), where a positive AMO is associated with basin-wide warming of the Atlantic sea surface and air temperatures, and with reductions in sea ice (Hanna et al., 2012; Zhang et al., 2019). Variations in air temperatures in West and Southeast Greenland and subsurface ocean temperatures over the last century, in particular, have been shown to be correlated with the AMO (Hanna et al., 2013; Straneo and Heimbach, 2013). In addition to interannual-to-multidecadal variability, these regions are also exhibiting rising air temperatures and sea-ice reduction associated with the amplification of climate change in the Arctic region (Serreze et al., 2009; Stroeve and Notz, 2018).

In terms of ocean properties, we note that the Ammassalik region is dominated by decadal to multi-decadal variability with no discernible long-term trend, while the ocean around Qaanaaq has recently warmed above the range exhibited over the last century (Figure 3). Recent trends in air temperature and sea ice in both regions are discernible when superimposed on the decadal to multidecadal variability (Figure 3a,b,e,f). A large air temperature warming trend that started in the 1990s (Figure 3a) and diminished beginning in the early 2000s (Hanna et al., 2021) is largely mirrored by a decreasing trend in sea-ice concentration (Figure 3c). Qaanaaq shows a larger reduction in sea-ice concentration than Ammassalik (Cooley et al., 2020), and glaciers in both regions have long been retreating. Helheim began retreating in the mid-2000s following a long period of stability and advance, whereas Heilprin has been retreating continuously since at least the 1920s (Figure 3g,h).

The historical data analysis also shows that present-day warm conditions are comparable to those of the 1930s–1940s (Figure 3), a warm period over the Atlantic and Arctic sectors (Polyakov et al., 2005; Box et al., 2009) that coincided with an AMO positive phase, which has been associated with glacier retreat around Greenland (Bjørk et al., 2012; Khan et al., 2020). The implication is that present-day conditions are not too dissimilar from the conditions that both communities experienced during the 1930s–1940s.

Ensemble projections from climate models indicate that, even in low greenhouse gas emission scenarios, the climate and the cryosphere in both regions are likely to move, within a few decades, beyond the ranges recorded for both communities over the last century (Figure 3). Considering the climate models' ensemble means, for example, mean annual air temperatures are projected to rise above the past 20 years' ranges by 2030–2040, and then warm still further by 2060 (Figure 3a,b). The ensemble means also project a reduction in sea ice (Figure 3e,f) and ongoing glacier retreat (Figure 3g,h; Goelzer et al., 2020), while a large spread in the climate model projections for ocean temperature indicates that the future evolution of ocean temperature is uncertain, particularly for Ammassalik (Figure 3c,d). Even considering the spread among climate model simulations, air temperature, sea ice, and glacier terminus position move outside of the range of contemporary human experience by 2060 (Figure 3). Over shorter lead times, the rate of change and emergence of unprecedented conditions will be influenced by the relative amplitudes of internal variability and by forced trends, which vary depending on location and the quantity that is of interest.

Past and Projected Changes in Ecosystems, Fisheries, and Humans

It is expected that projected changes in the physical climate will impact both the shelf areas and the fjords in the Qaanaaq and Ammassalik regions and, in turn, affect the ecosystems and human communities that depend on them (Figure 4). For example, increased subglacial discharge will augment the glacial nutrient pump as long as a glacier is grounded in deep, nutrient-rich waters. Once the glacier retreats into shallower waters, however, the nutrient source for the upper waters of the fjord and shelf is expected to be reduced (Meire et al., 2017; Hopwood et al., 2020). Sea-ice variability will also

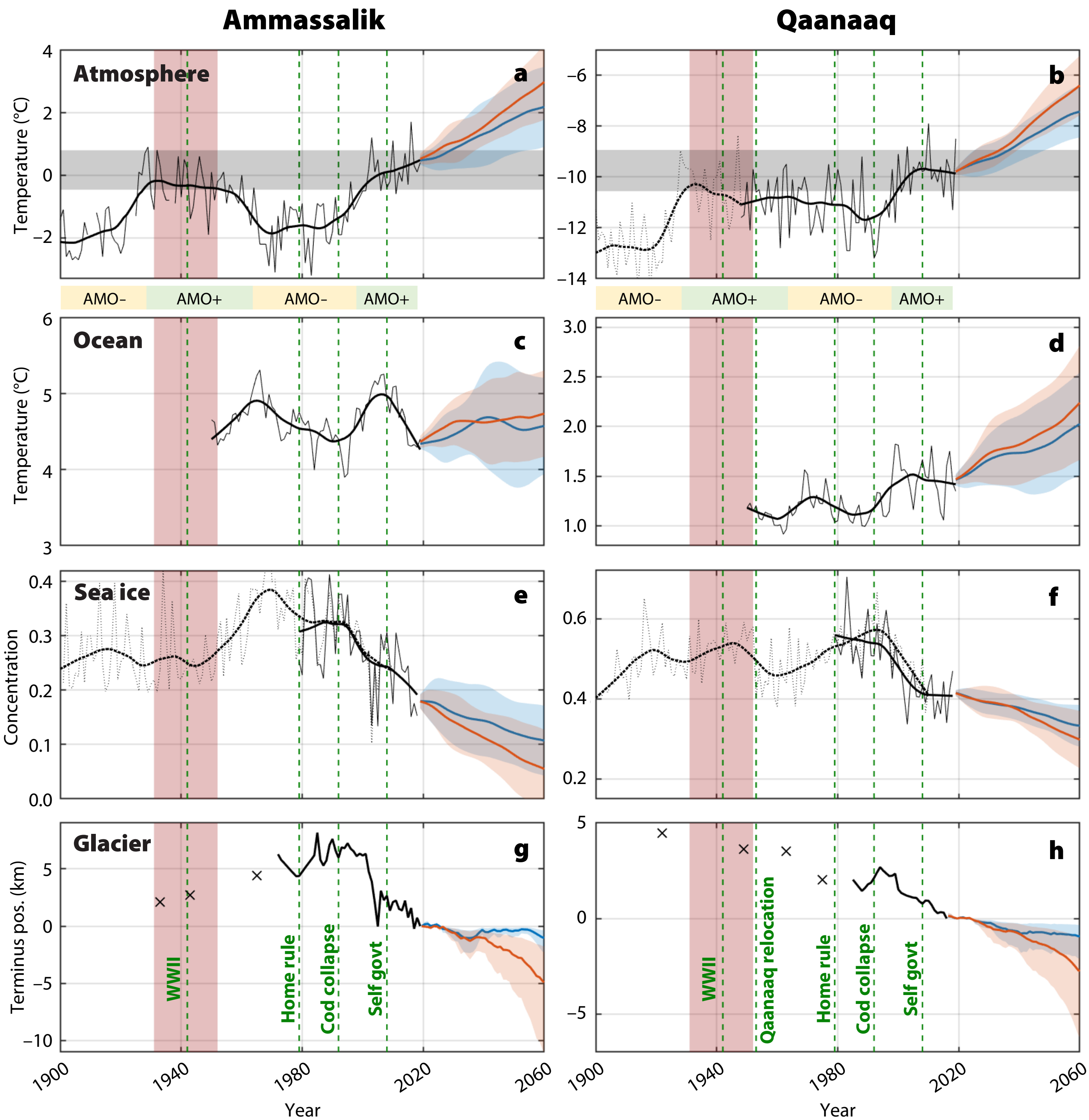

FIGURE 3. Past and projected future variability for the main physical climate components for the social-ecological systems in Ammassalik (left) and Qaanaaq (right), together with examples of societal events relevant to Greenland (green vertical dashed lines). (a, b) Air temperature. Past air temperatures are derived from weather stations (Cappelen et al., 2019), with annual values shown as a thin black line and a 20-year centered mean shown as a thick black line. In Qaanaaq prior to 1948, we use data from nearby Upernavik, shown as dashed lines. The future projections are derived from an ensemble of Coupled Model Intercomparison Project Phase 6 (CMIP6) and show an ensemble mean (thick line) and ensemble standard deviation (shading) for low emission (ssp245, blue; ssp = shared socioeconomic pathways) and high emission (ssp585, red) scenarios. Gray horizontal shading on the air temperature plots shows the observed range over the past 20 years. The red vertical shading on all plots highlights the 1930s and 1940s warm period, while the colored bars beneath the plots show the positive and negative phases of the Atlantic Multidecadal Oscillation (AMO). (c,d) Equivalent for 200–500 m ocean temperature. Past ocean temperatures are derived from the EN4 subsurface temperature and salinity data set (Good et al., 2013) for the Irminger Sea (Ammassalik) and Baffin Bay (Qaanaaq) regions. (e,f) Annual mean sea-ice concentration over regions close to the communities. The solid lines show satellite-derived values (Peng et al., 2013) while the dashed lines come from the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS)-20C model (Schweiger et al., 2019). (g,h) Glacier terminus positions refer to Helheim Glacier (for Ammassalik) and Heilprin Glacier (for Qaanaaq), with data from Khan et al. (2020) and Sakakibara and Sugiyama (2018). The glacier projections use a terminus retreat parameterization described in Slater et al. (2019). The future projections have had a constant bias subtracted to ensure continuity with recent observations; in this sense, the projections should really be interpreted as anomalies relative to the recent past.

impact shelf productivity, with longer periods of ice-free conditions supporting higher rates of productivity, as already observed for Baffin Bay and the Arctic Ocean (Frey et al., 2020; York et al., 2020). At present, the productivity data for both regions is limited to a few decades over which significant interannual variability exists but no significant trend emerges (Figure 4a,b). One of the challenges to understanding the evolution of these systems will be identification of the factors governing productivity over longer lead times. Globally, biomass is predicted to decline under all emission scenarios due to increasing temperatures and decreasing global primary production (Lotze et al., 2019); Greenland and other high-latitude regions, however, are expected to respond differently (Wassmann and Registad, 2011; Oksman et al., 2022).

The existing fisheries records of catch for the two regions are too short to identify clear trends or investigate how their variability relates to shifting environmental conditions over the last few decades (Figure 4c,d). In the future, further insight may be gained through co-production of knowledge that integrates the memory of the community with knowledge of climate variability. Here, we summarize what is known and include several considerations that highlight some of the mechanisms that can influence fisheries variability.

The Greenland fishing industry, particularly on the east coast, is poised to grow in the coming years as some of the distribution ranges of commercially harvested species continue to shift northward into newly productive waters. In Southeast Greenland, for example, the value of Greenland halibut commercial fisheries now accounts for the largest part of the economy (47% on average between 2012 and 2020), surpassing ringed seal (31%) and harp seal (11%), which were the most important species in the past in terms of coastal resources (Figure 4c). This is also evident in the last decade with the increase in catch of pelagic species offshore, such as capelin, blue whiting, herring, and mackerel. Cod catches in East Greenland are also expected to increase due to new spawning aggregations identified at Kleine Bank (offshore of Ammassalik) and greater transport and migration of cod eggs, larvae, and juveniles from Icelandic waters. As a result, Tasiilaq is being considered as the location for a new processing industry. However, it is unclear how new offshore fisheries (e.g., mackerel and other pelagic fish) or existing ones (cod) will evolve.

Qaanaaq and Ammassalik differ from the rest of Greenland in that marine mammal harvesting is very important for food security, culture, and the local economy in these two communities (Figures 2e and 4c,d). In Qaanaaq, traditional and sustenance activities (marine mammal hunting, winter ice fishing for Greenland halibut, and seabird harvesting) will most likely decline with climate change for numerous reasons, among them ice cover limiting access to ice-associated activities and species, shifts in zooplankton assemblages from dominance of larger Arctic species (e.g., *Calanus glacialis*, *Calanus hyperboreus*) to smaller subarctic/boreal species (e.g., *Calanus finmarchicus*; Møller and Nielsen, 2020), and replacement of Arctic cod by forage fish of boreal origin such as capelin and sand lance. These changes carry the potential to impact the food security and economy of local communities and should therefore be closely monitored and considered in community planning exercises. Although increased opportunities for commercial fishing for Greenland halibut may improve employment and the economy in these communities, there is much uncertainty about the processes that regulate distribution and abundance of these species. For example, Greenland halibut in Upernavik, Uummannaq, and Disko Bay areas show signs of overfishing, as evidenced by a decrease in the mean length of the landed fish (NAFO, 2020). These various points illustrate not only the potential impacts of climate change on fisheries but also the ways in which government regulations, available knowledge, markets, fishing technologies and practices, and environmental conditions all intersect to influence communities, fisheries, and the coastal social-ecological systems.

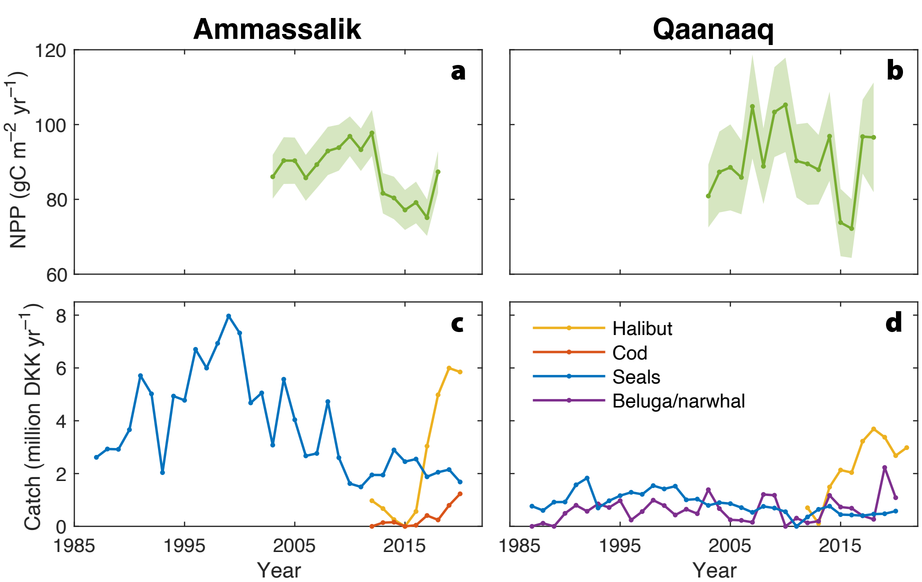

FIGURE 4. Interannual variability in net primary productivity (NPP), fish catch, and marine mammal hunting (a,b). Annual primary production ± standard deviation of monthly means is plotted in gC m^{-2} yr^{-1} on the shelf and shelf break. Data are based on weekly averages of multi-sensor satellite ocean color composites (as in Vernet et al., 2021) for the (a) Ammassalik and (b) Qaanaaq (including the North Water Polynya) regions. Note similarity in rates at the two locations separated by 15° of latitude. Fish catch and hunting of seals and beluga/narwhal are shown in millions of Danish kroner per year in inshore waters of (c) Ammassalik and (d) Qaanaaq (Statistics Greenland, 2020).

DISCUSSION

The confluence of Arctic and Atlantic currents, synoptic wind events, glaciers, and sea ice creates conditions that foster healthy and rich ecosystems in Greenland's glacial fjords and continental shelf waters. Processes such as the topographically induced mixing and upwelling at glaciers' termini enrich the surface waters with nutrients. Seasonal sea-ice melt sets the timing for the phytoplankton blooms that characterize these regions. Greenland's large latitudinal range, spanning Arctic and subarctic regions, results in large spatial variations in climate, land and marine-terminating glaciers, and sea-ice cover. Greenland's coastal margins are characterized by diverse ecosystems that support polar and subarctic species. The locations of settlements around Greenland are, to a large extent, influenced by the availability of these marine resources.

Climate change is rapidly affecting the different processes that foster healthy ecosystems around Greenland. The two locations we focus on here have distinct climates. Ammassalik is strongly influenced by the Atlantic Ocean, with mild winters and a long sea ice-free season. Qaanaaq is Arctic in character, with long cold winters and a short sea ice-free season. Yet, both are affected by substantial multidecadal and interannual variability in air and ocean temperatures and sea-ice conditions. The contemporary climate has some precedent within recent human memory due to a warm period during the 1930s to 1940s, but by the middle of the twenty-first century the climate and cryosphere will almost certainly move beyond contemporary experience. Predicting precisely how the physical climate will evolve in the coming decades, and its impact on the cryosphere, ecosystems, and human communities, remains challenging for a number of reasons. Chief among them is the coupling between systems; for example, a retreat and shoaling of marine-terminating glaciers (itself challenging to predict) may impact marine ecosystems and fisheries through reduced nutrient upwelling, but such links are poorly understood. Some insight may be gained from assessing how past variability has played a role in any ecosystem or human system change. However, this study shows that while we have enough data to reconstruct the regional, physical climate variability over the last century and—assuming an understanding of linkages—how this may have resulted in conditions that support life at Greenland's margins—there are not enough data to reconstruct the ecosystem variability. Key to future understanding, therefore, is the collection of long-term local and regional ecosystem and fisheries data and the integration, and co-production, of knowledge with local communities. For future projections, there are also issues of scale; the climate models used for projection do not resolve the processes and details of Greenland's coastline, and it therefore remains unclear how well these models reflect local conditions. Furthermore, collaborative approaches are needed to investigate the evolution of the social-ecological systems that include hunters and fishers (e.g., Planque et al., 2019; Mathis et al., 2015).

The social-ecological system at Greenland's margins is changing in response not only to global climate change but also to other processes, with varying impacts across the country. Tourism and scientific research in Greenland increasingly bring outsiders to the island, benefiting some through new jobs but also disrupting others—docking of cruise ships and accompanying infrastructure may favor tourists rather than residents. In recent decades, new government regulations have, in some cases, had more profound impacts on local hunting and fishing than has climate change. At the same time, sea-ice loss can sometimes allow greater access to harbors and open up new areas to lucrative mining, while in other cases thinning sea ice thwarts hunting, travel, and transportation. Changes in the social-ecological systems are uneven and inconsistently distributed across the Greenland population. They need to be understood in their own contexts (local, national, global) and by recognizing interacting human and biophysical processes. The development of participatory scenarios with multiple stakeholders (hunters, fishers, natural scientists, social scientists, policymakers) to anticipate future changes in these marine social-ecological systems will be key to providing contextual information for adaptive planning.

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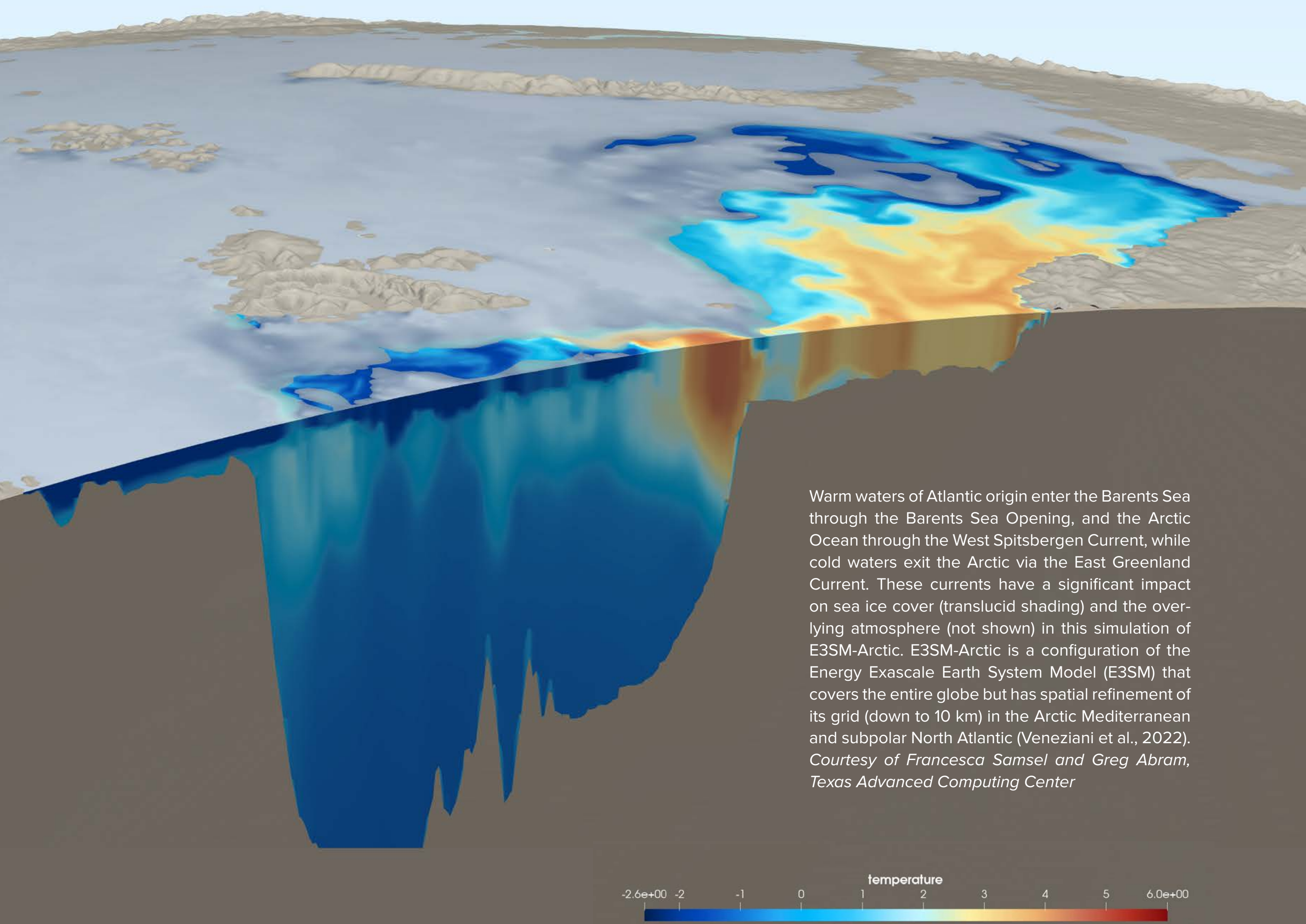
INTERACTIONS BETWEEN THE ARCTIC MEDITERRANEAN AND THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

A REVIEW

By Wilbert Weijer, Thomas W.N. Haine, Ali H. Siddiqui, Wei Cheng, Milena Veneziani, and Prajvala Kurtakoti



Warm waters of Atlantic origin enter the Barents Sea through the Barents Sea Opening, and the Arctic Ocean through the West Spitsbergen Current, while cold waters exit the Arctic via the East Greenland Current. These currents have a significant impact on sea ice cover (translucid shading) and the overlying atmosphere (not shown) in this simulation of E3SM-Arctic. E3SM-Arctic is a configuration of the Energy Exascale Earth System Model (E3SM) that covers the entire globe but has spatial refinement of its grid (down to 10 km) in the Arctic Mediterranean and subpolar North Atlantic (Veneziani et al., 2022). *Courtesy of Francesca Samsel and Greg Abram, Texas Advanced Computing Center*

ABSTRACT. The Atlantic Meridional Overturning Circulation (AMOC) plays a significant role in the global climate system, and its behavior in a warming climate is a matter of significant concern. The AMOC is thought to be driven largely by ocean heat loss in the subpolar North Atlantic Ocean, but recent research increasingly emphasizes the importance of the Arctic Mediterranean for the AMOC. In turn, the AMOC may influence the Arctic heat budget through its impact on poleward heat transport. Hence, understanding the processes that link the AMOC and the Arctic is critical for our ability to project how both may evolve in a warming climate. In this paper we review some of the recent research that is shaping our thinking about the AMOC and its two-way interactions with the Arctic.

INTRODUCTION

The Atlantic Meridional Overturning Circulation (AMOC) is one of the most important circulation components in Earth's climate system. It transports buoyant waters northward in the upper 1,000 m of the Atlantic Ocean to the high-latitude North Atlantic and the subarctic seas, where these waters are transformed by strong heat loss and by several processes that affect their salinity, such as meltwater input and brine rejection. The resulting dense waters are then transported southward throughout the Atlantic at depths between 1 km and 3 km and subsequently dispersed throughout the Southern Ocean and the Indo-Pacific Ocean (see Buckley and Marshall, 2016, for a review).

By transporting heat and salt northward throughout the Atlantic Ocean, the AMOC plays a key role in sequestration of anthropogenic heat and carbon (Fontela et al., 2016), thus mitigating global warming. Outside of the tropics, the contribution of the ocean to total meridional heat transport is relatively small (<20%) compared to that of the atmosphere (Trenberth et al., 2019); however, it has significant climate implications due to the AMOC's long-term memory, which manifests itself as variability on decadal and multidecadal timescales (R. Zhang et al., 2019) and a delayed response to anthropogenic forcing (Weijer et al., 2020). In fact, changes in the operation of the AMOC have been implicated in the well-documented climate swings during the last ice age—known as Dansgaard/Oeschger cycles and Heinrich events—and the rapid transitions between the Bølling–Allerød and Younger Dryas events at the end of the last glacial period (Broecker et al., 1985; Lynch-Stieglitz, 2017). Uncertainties about the fate of the AMOC in a warming climate (Weijer et al., 2020), and even the possibility of a collapse (Weijer et al., 2019), make a thorough understanding of the AMOC and its drivers imperative for our ability to anticipate future changes in our climate system.

In recent decades, the role of the Arctic Mediterranean[1] as the northernmost terminus of the AMOC and the two-way interactions between the AMOC and the northern seas have come into focus. Several long-term monitoring programs have improved our estimates of the AMOC and the associated exchanges of water, heat, and salt. The Rapid Climate Change/Meridional Overturning Circulation and Heatflux Array (RAPID/MOCHA) has been monitoring the strength of the AMOC at 26.5°N since 2004 (Cunningham et al., 2007), while the Overturning in the Subpolar North Atlantic Program (OSNAP) array has been measuring the AMOC in the subpolar North Atlantic (SPNA) since 2014 (Lozier et al., 2019; Li et al., 2021). Other monitoring programs measure transports across several sections of the Greenland-Scotland Ridge (GSR; Østerhus et al., 2019), through Fram Strait (Karpouzoglou et al., 2022) and the Barents Sea Opening (Skagseth et al., 2008), and in the Nansen and Amundsen Basins of the Arctic Ocean (Pnyushkov and Polyakov, 2022, in this issue). At the same time, the number of autonomous drifting Argo floats, which observe the temperature and salinity of the upper 2 km, has been increasing since 1999 (Jayne et al., 2017). Other important progress has been made in the development of better ocean models (Fox-Kemper et al., 2019) that can be quite realistic (Haine et al., 2021).

In this paper, we review some recent advances in our understanding of these linkages, particularly in the last decade. We conclude by outlining prominent challenges and opportunities.

LINKING THE AMOC AND THE ARCTIC MEDITERRANEAN

The surface branch of the AMOC is most focused in the Gulf Stream, the fast western boundary current that moves northward along the east coast of North America (Figure 1). Separating at Cape Hatteras, it continues northeastward, rounds the corner at the Grand Banks, and continues to the northeast as the North Atlantic Current (NAC). In the eastern North Atlantic Ocean (ENA), the NAC bifurcates: a significant fraction recirculates southward and then westward to feed the Gulf Stream in the subtropical gyre, while roughly 15 Sv (1 Sv = 10^6 m^3 s^{-1}) escapes northward and skirts the eastern boundary of the subpolar gyre. Some of this water joins the subpolar gyre and flows west as the Irminger Current. About 8 Sv cross the GSR, the undersea ridge system that connects Greenland, Iceland, the Faroe Islands, and Scotland (Østerhus et al., 2019; Figure 2).

Although how much of the water that flows into the Nordic Seas is derived from the subtropics is not known in detail, nor are the mechanisms that control it, a picture has emerged of the ENA as a "switchyard" (region of changing currents) for the waters flowing into the Nordic Seas (Figure 3). Hátún et al. (2005) argue that the strength and the extent of the subpolar gyre influence the waters flowing

[1] In this paper we use the "Arctic Mediterranean" or "Arctic" to refer to the combined Arctic Ocean proper, the Nordic Seas, the Canadian Arctic Archipelago, and Baffin Bay.

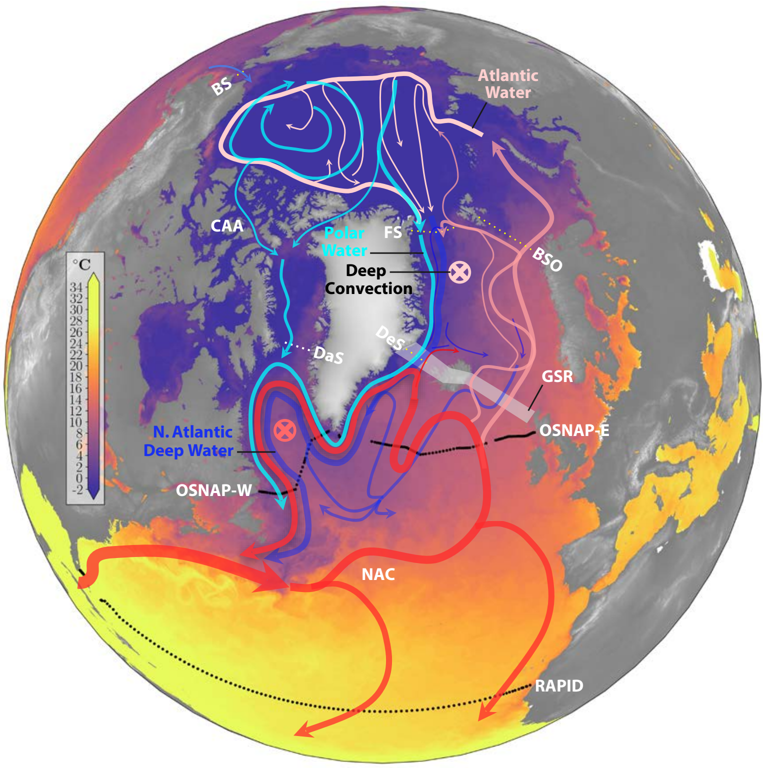


FIGURE 1. Schematic of the horizontal circulation in the North Atlantic and Arctic Mediterranean. The Polar Water (cyan) lies at the surface, the North Atlantic Deep Water (blue) lies at depth, and the Atlantic Water from the North Atlantic Current lies at the surface in the Atlantic and Nordic Seas and at intermediate depth in the Arctic Ocean (red and pink). The Rapid Climate Change (RAPID) and Overturning in the Subpolar North Atlantic Program (OSNAP) arrays are shown with black dots. The base map shows sea surface temperature for June 2021 (from Group for High Resolution Sea Surface Temperature [GHRSST]; JPL Mur MEaSUREs Project, 2015). See also Figure 2, which emphasizes the vertical overturning circulation. BS = Bering Strait. CAA = Canadian Arctic Archipelago. FS = Fram Strait. BSO = Barents Sea Opening. DaS = Davis Strait. DeS = Denmark Strait. GSR = Greenland-Scotland Ridge. NAC = North Atlantic Current.

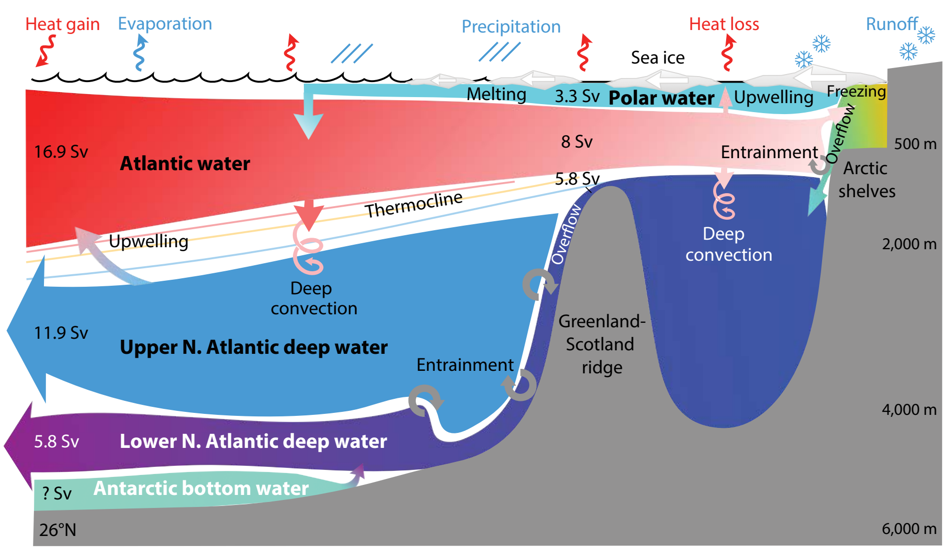


FIGURE 2. Schematic of the overturning circulation in the North Atlantic and Arctic Mediterranean. Transports at 26°N are from the RAPID array (Frajka-Williams et al., 2021), except for the Antarctic bottom water value, which is uncertain but small. Transports at the Greenland-Scotland Ridge are taken from Østerhus et al. (2019). The Polar Water value includes the Canadian Arctic Archipelago throughflow, and the net flow across the Greenland-Scotland Ridge includes flow from the Pacific through Bering Strait, runoff, and precipitation minus evaporation.

over the GSR. Cool and fresh subpolar waters dominate the ENA when the subpolar gyre is strong and expansive, usually during periods of persistent positive North Atlantic Oscillation (NAO, a prominent pattern of atmospheric variability in the westerly winds and storm track over the North Atlantic Ocean). When the subpolar gyre is weak and contracted (during negative phases of the NAO), warm and salty subtropical waters flood the ENA, increasing temperature and salinity in the Atlantic Water (AW) flowing into the Nordic Seas. Koul et al. (2020) confirm this picture by using a Lagrangian particle tracking method to study the sources of the waters in the ENA, concluding that between 50% and 70% are derived from the subtropics, depending on the state of the subpolar gyre. Other patterns of variability have been identified as important controls on the transport across the GSR, in particular, the East Atlantic Pattern (Heuzé and Årthun, 2019).

Once in the Norwegian Sea, AW is transported northward with the Norwegian Current. Part of this flow recirculates in the Nordic Seas while the rest flows into the Arctic Ocean through the Barents Sea Opening (2.3 Sv) and Fram Strait (2.6 Sv; estimated from Figure 4 in Tsubouchi et al., 2018). What controls the transport of AW into the Barents Sea, and into the Arctic Ocean through Fram Strait is imperfectly known, but the role of regional wind stress patterns has emerged as a leading driver (Lien et al., 2013; Chafik et al., 2015).

In the Nordic Seas and the Arctic Ocean, AW is subjected to intense surface cooling and freshening that transforms it into other forms (Figure 2). In the Greenland Sea, the recirculating salty AW is cooled by the atmosphere, leading to deep overturning that can cool the water column down to several kilometers' depth. How much this process contributes to the overflow waters is still a matter of debate (R. Zhang and Thomas, 2021). The water mass transformations in the Arctic Ocean are often described in the context of the double-estuarine model of

Arctic overturning (Rudels, 2010; Eldevik and Nilsen, 2013; Haine, 2021; see also Rudels and Carmack, 2022, in this issue). According to this model, part of the AW inflow is cooled by heat loss to the atmosphere and freshened by freshwater inflow through Bering Strait, sea ice melt, precipitation, and runoff, generating a relatively buoyant water mass called Polar Water. This water flows towards the SPNA through Fram Strait and Denmark Strait as the East Greenland Current, and also through the Canadian Arctic Archipelago (CAA) and Davis Strait. Another fraction of AW is cooled and mixed with dense and salty waters from the extensive and shallow shelf regions, where sea ice formation leads to brine rejection and salinification (Rudels and Quadfasel, 1991). A third transformation product of AW interacting with the atmosphere is sea ice, which is exported to the SPNA with the Polar Water.

The dense water masses formed in the Arctic Ocean flow southward through Fram Strait, which is the only deep connection between the Arctic Ocean and the Nordic Seas. There they mix with water masses formed in the Greenland Sea and cross the GSR into the SPNA as distinctive overflows known as Denmark Strait Overflow (DSOW) and Iceland Strait Overflow Water (ISOW; Østerhus et al., 2019). Upon entering the SPNA, these overflow waters mix with ambient waters to form lower North Atlantic Deep Water (NADW), which flows southward as the deepest branch of the AMOC. The slightly-less-dense ambient waters, called upper NADW, are formed in the Labrador and Irminger Seas by deep convection and are also exported south in the deep branch of the AMOC (Figure 2).

Although the pathways and transport estimates are reasonably well constrained based on data from the monitoring efforts, details of the processes that lead to water mass transformations, overflows, and entrainment are still poorly understood. They depend on small-scale and often episodic processes that are extremely difficult to observe, especially given their propensity to occur during the harsh conditions of polar winter. They are also challenging to capture in numerical models because the small spatial scales noted defy explicit representation, necessitating the use of parameterizations (Hewitt et al., 2022).

IMPACTS OF THE AMOC ON THE ARCTIC

The RAPID/MOCHA and OSNAP arrays have shown that the AMOC varies on timescales from seasonal to at least decadal. On interannual timescales, most spectacularly, RAPID recorded a significant weakening of the AMOC at 26.5°N in the winter of 2009/2010. On decadal timescales, the AMOC at this latitude appears to have undergone a weakening of its mean strength by about 2.5 Sv after the first four years of monitoring and appears to have been steady since then (Smeed et al., 2018; Moat et al., 2020). It is unclear, however, whether this weakening is part of a multidecadal variation or signifies a gradual decline. Indeed, climate models almost unanimously project a weakening of the AMOC in the twenty-first century in response to anthropogenic forcing (Cheng et al., 2013; Weijer et al., 2020), and some studies claim that such a weakening is already in progress (Caesar et al., 2018, 2021; but see Kilbourne et al., 2022, for an alternate view). On the other hand, the weakening could be part of multidecadal variability, as climate models clearly demonstrate that the AMOC can display internal variability on multidecadal timescales. This could be due to a slow ("reddening") response to atmospheric variability, most notably that associated with the NAO (Delworth et al., 2017). Other studies point to the possibility of the resonant excitation of an internal mode of ocean dynamics (Dijkstra et al., 2006). Unfortunately, models simulate a wide range of AMOC

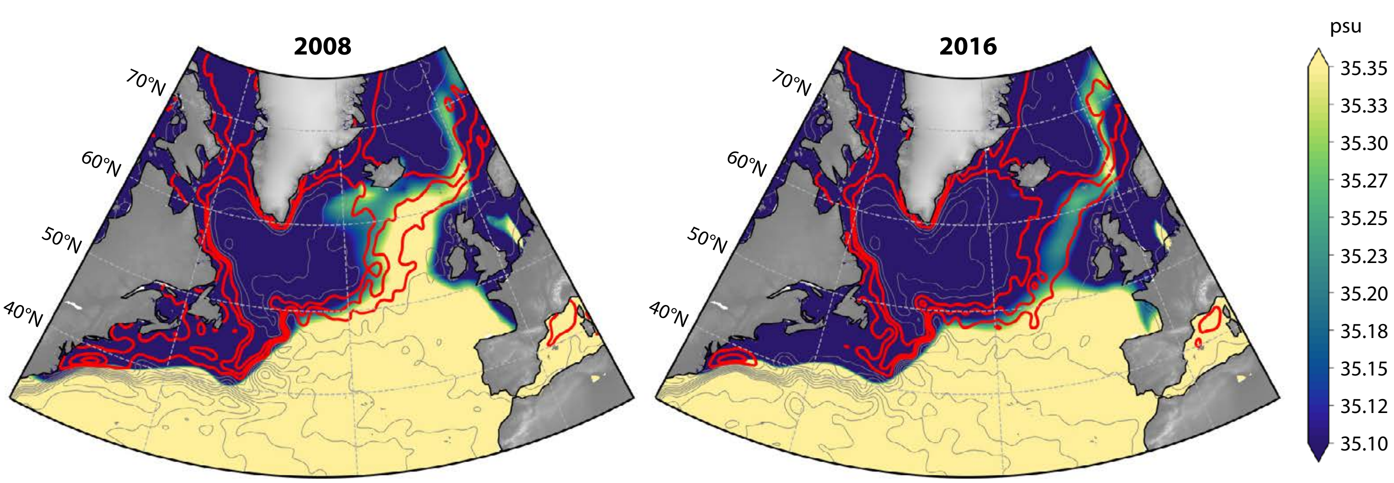


FIGURE 3. Interannual variations in the eastern North Atlantic Ocean (ENA) modulated by the North Atlantic Current flow into the Nordic Seas. Colors show annual-average surface salinity (from EN4; Good et al., 2013) for 2008 and 2016, which correspond to saline and fresh years in the ENA. Contours show the average absolute dynamic topography (from AVISO) for the preceding two years (2006–2007 and 2014–2015), which correspond to contracted and expanded subpolar gyre states. The contours are from –0.8 to 0.8 m with a spacing of 0.1 m and are smoothed with a Gaussian filter with scale 400 km. The red contours (–0.3, –0.2, and –0.1 m) depict the path of the North Atlantic Current.

variability on these timescales and no consensus has yet emerged (Muir and Fedorov, 2017).

Given that changes in AMOC strength directly impact northward heat transport, both in the subtropical (Johns et al., 2011) and subpolar regions (Lozier et al., 2019), how does AMOC variability and trends at lower latitudes impact heat transport toward the Arctic? Several studies have tried to address this question, using different approaches. Bryden et al. (2020), for instance, analyzed the consequences of the AMOC slowdown after 2009 and concluded that its weakened state has indeed led to a reduction in meridional heat transport of 0.17 PW (about 15%) in northward heat transport across 26.5°N. They demonstrate that this has led to significant cooling of the eastern subpolar gyre, extending all the way to Iceland. However, whether this has led to reduced heat flux into the Nordic Seas is still a matter of debate. Rossby et al. (2020) analyzed a century's worth of hydrographic observations and although they found no evidence for a long-term trend, they did find that northward volume and heat transport across the GSR indeed started to decline around 2010. On the other hand, Tsubouchi et al. (2021) conclude that heat transport into the Nordic Seas is *decoupled* from the mid-latitude AMOC. They estimate ocean heat transport across the GSR for the period 1993–2016 using a box inverse method and argue that a sudden increase in poleward heat transport after 2001 is inconsistent with the apparent weakening of the AMOC at 26.5°N since 2004. Longer time series of AMOC strength and heat transport are needed to settle this debate.

Inflow of warm waters of Atlantic origin strongly influence climate conditions, especially in the Barents and Kara Seas (e.g., Smedsrud et al., 2013; Asbjørnsen et al., 2019). Indeed, the well-publicized "Atlantification" of the Arctic (Polyakov et al., 2017), which describes increased presence and shoaling of AW in the Eurasian Basin, appears to be consistent with this process. Atlantification is associated with weakening upper-ocean stratification, increased upper-ocean current speeds and ocean heat loss, and less sea ice in the Eurasian Basin (Polyakov et al., 2020b,c). Atlantification may also cause biogeochemical changes in this area (Polyakov et al., 2020a). Still, it remains unclear how anomalies in the northern Nordic Seas connect to AMOC variability at lower latitudes. Temperature anomalies have been traced back from Svalbard to the SPNA in both satellite data (Chepurin and Carton 2012) and reanalysis products (Figure 4; Årthun et al., 2017), as well as in climate models (Årthun and Eldevik, 2016). The propagation of sea surface temperature (SST) anomalies from the Grand Banks off Newfoundland to Svalbard takes about a decade, while sea ice response lags SST anomalies in the Norwegian Sea by roughly three years. Årthun and Eldevik (2016) conclude that the heat content anomalies coming from the SPNA mainly involve changes in circulation rather than temperature, and also point to a decadal timescale for anomalies to reach the Arctic from the subpolar North Atlantic. Based on an analysis of high-resolution climate models,

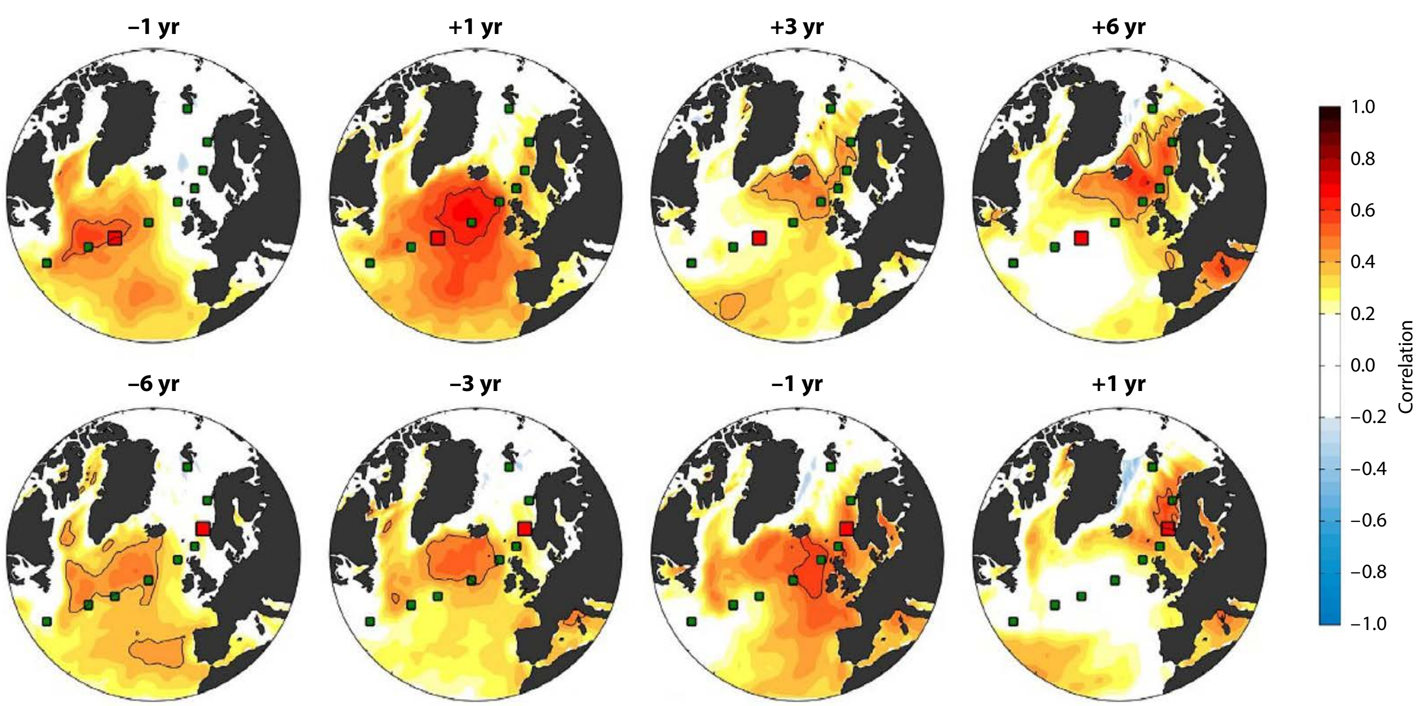


FIGURE 4. Coherent propagation of sea surface temperature (SST) anomalies from the subpolar North Atlantic (SPNA) to the Barents Sea. Shading shows lagged correlations between SST throughout the SPNA and Nordic Seas, and SST at two select stations, indicated by red squares (SST from the Hadley Centre SST product; Rayner et al., 2003). The upper row shows data for a station in the subpolar gyre, and the lower row for a station in the Norwegian Sea. Positive (negative) values of the lag means that the SST at the selected station leads (lags) the field. Green squares denote other stations defined in the original paper to track the propagation of SST anomalies. *From Årthun et al. (2017), licensed under CC BY*

Docquier et al. (2019) confirm the importance of oceanic heat transport (OHT) by AW for sea ice conditions in the Arctic, but caution that the OHT-sea ice relationship is weaker for OHT at lower latitudes.

It also seems that the direct link between AMOC strength and heat supply to the Arctic breaks down under increased greenhouse forcing. In particular, climate models simulating future scenarios almost unanimously project a *decrease* in the strength of the AMOC (Figure 5), but often an *increase* in OHT into the Arctic (e.g., Hwang et al., 2011). Models agree that this is a consequence of a reduction in ocean heat loss in the Nordic Seas that allows warmer waters to reach the Arctic, in spite of a reduced heat supply from lower latitudes (Nummelin et al., 2017; Oldenburg et al., 2018); in other words, a trade-off between reduced supply of warmer waters is won—at least at Arctic latitudes—by ocean warming (Liu et al., 2020). Some studies also point to a strengthening of the gyre circulation in the Nordic Seas (Lique and Thomas, 2018).

However, modeling studies suggest other mechanisms may be important. Most of these studies explore the connections between the AMOC and Arctic sea ice using correlation analysis and conclude that mid-latitude AMOC leads Arctic sea ice by just a few years (Mahajan et al., 2011; Day et al., 2012). In addition, several modeling studies report stronger correlations between Arctic sea ice and the Atlantic Multidecadal Oscillation (AMO) than with AMOC (e.g., Day et al., 2012). The AMO is a mode of SST variability in the North Atlantic that is thought to be strongly linked to the AMOC as periods of stronger AMOC are associated with positive SST anomalies in the North Atlantic Ocean and Nordic Seas (Knight et al., 2005; R. Zhang et al., 2019; Fraser and Cunningham, 2021). This suggests that an alternative mode of AMOC influence on the Arctic may be through atmospheric teleconnections, in particular, in response to the AMO.

IMPACTS OF THE ARCTIC ON THE AMOC

As discussed in the previous sections, water mass transformations in the Nordic Seas and the Arctic Ocean are key processes that feed the dense lower limb of the AMOC. Consequently, interruptions in these processes can have far-reaching consequences. One intriguing possibility is a potential heat crisis in the Arctic that would shut down the shallow estuarine cell. Based on simple budget calculations of the Arctic double-estuarine model, Haine (2021) argues that under certain conditions the double-estuarine model can no longer satisfy the heat budget of the Arctic Ocean. Both increased heat input from AW and increased stratification from enhanced precipitation could push the Arctic toward such a heat crisis. This scenario may be consistent with Atlantification. Similarly, the idea that the AMOC in a warming climate reaches further into the Arctic Ocean was already noted by Bitz et al. (2006), and a northward shift of the regions of deep convection was anticipated by Lique and Thomas (2018). How this transition would affect the volume and properties of the deep overflow waters that feed into the deep branch of the AMOC at lower latitudes is not known at present.

Observational studies (Moore et al., 2015; Våge et al. 2018) have hinted that a retreating marginal ice zone in the Greenland and Iceland Seas may have consequences for deep water formation in the Nordic Seas. However, the water mass patterns that feed into the DSOW from the Nordic Seas and the processes behind them are complex. Indeed, a recent modeling study by Wu et al. (2021) paints a complicated picture in which the effects

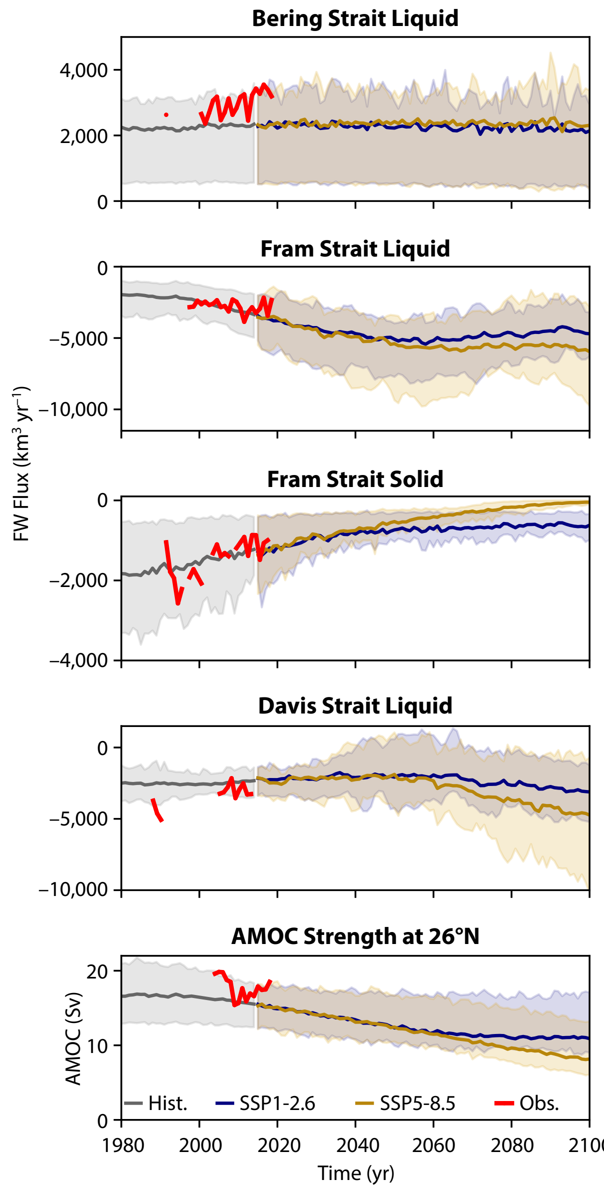


FIGURE 5. Arctic freshwater (FW) fluxes and 26°N Atlantic Meridional Overturning Circulation (AMOC) strength from CMIP6 models and observations. The CMIP6 liquid and solid freshwater fluxes across key Arctic gateways (top four panels; see Figure 1 for locations) are taken from Zanowski et al. (2021). Minor fluxes from other gateways are not shown. The corresponding CMIP6 AMOC strengths (bottom panel) are taken from Weijer et al. (2020). In each case, historical CMIP6 data, SSP1-2.6, and SSP5-8.5 projections are shown (ensemble spread and ensemble mean with the lines). In each panel, available observations are plotted in red (Curry et al., 2014; de Steur, 2018; Woodgate, 2018; Frajka-Williams et al., 2021; Karpouzoglou et al., 2022; Sumata et al., 2022). Note the different y-axes.

of internal variability in sea ice coverage are teased out from the effects of changes in sea ice, atmospheric-ocean fluxes, and ocean stratification due to anthropogenic forcing. The study shows that, in a warming climate, deep convection is reduced in the Greenland Sea gyre because of a decreased temperature difference between the ocean surface and the atmosphere above it, and because of increased ocean stratification. On the other hand, convection is enhanced within the East Greenland Current because of the retreating sea ice edge, with a possible impact on Denmark Strait waters directly downstream. Therefore, a shift in where deep water is created in the Nordic Seas under changing climate conditions may impact the AMOC in subtle but critical ways that require additional investigation in future studies.

Several sources and reservoirs of Arctic freshwater that are releasing more freshwater in a warming climate can affect the AMOC by freshening surface waters in the SPNA, Nordic Seas, and Arctic Ocean and thereby weakening deep convection and upper NADW formation (Figure 2; Carmack et al., 2016; see Figure 5 for key freshwater gateway fluxes from climate models and observations). First is the source of freshwater from the atmosphere, via precipitation and runoff, which is projected to increase in the twenty-first century as the hydrological cycle accelerates (Haine et al., 2015). Second is the freshwater flux to the Arctic Ocean through Bering Strait, which has been increasing in recent years (Woodgate, 2018; Figure 5).

Third is the Beaufort Gyre, which switches between a cyclonic and anticyclonic circulation state on a decadal timescale, thereby releasing and accumulating freshwater (Proshutinsky et al., 2015). The Beaufort Gyre has been in a persistent anticyclonic state since 1997, resulting in an accumulation of 6,400 km^3 of liquid freshwater from 2003 to 2018 alone (the period of high-quality oceanographic observations; Proshutinsky et al., 2019). There has been an associated increase in Beaufort Gyre stratification, contrasting with the decrease in Eurasian Basin stratification due to Atlantification (Hordoir et al., 2022). J. Zhang et al. (2021) studied the potential impacts of releasing this freshwater by looking at past analogs of freshwater accumulation and release episodes by the Beaufort Gyre. By comparing previous periods of rapid freshwater release (1983–1995) and accumulation (1997–2008), they found that the Beaufort Gyre freshwater release, equivalent to about 0.02 Sv, comparable to current input from the Greenland Ice Sheet (GrIS; Böning et al., 2016), has the potential to lower salinities in the Labrador Sea by as much as 0.4. Indeed, climate models project increasing freshwater liquid fluxes through Fram and Davis Straits (Figure 5).

Fourth is the GrIS, which contains almost 3 million cubic kilometers of freshwater (Frajka-Williams et al., 2016; see also Wouters and Sasgen, 2022, in this issue, and Briner, 2022, in this issue). A recent assessment indicates that by 2016 the Greenland Ice Sheet and surrounding land ice had lost roughly 6,300 km^3 of ice, and that the annual rate of freshwater discharge is equivalent to 0.04 Sv (Bamber et al., 2018), providing an important source of freshwater to the ocean. Large uncertainty exists about how the GrIS freshwater leaves the fjords and coastal ocean. Nevertheless, when Böning et al. (2016) studied the potential impacts of GrIS freshwater release in an eddy-resolving ocean model, they concluded that it had not yet significantly impacted the AMOC, but that a slowdown is inevitable as GrIS melting continues to accelerate.

One intriguing process through which the Arctic may influence the AMOC is through a reduction in sea ice cover (seen in Figure 5 as a decrease in Fram Strait solid freshwater flux). In particular, Sévellec et al. (2017) argue that a reduction in sea ice exposes more ocean to radiative warming (an effect known as the ice-albedo feedback) that increases the buoyancy of the Arctic surface waters. Once these warmer waters reach the SPNA, they may lead to a suppression of deep convection and a weakening of the AMOC. Similarly, changes in the seasonal cycle of sea ice might also have an effect on the buoyancy of the Arctic surface waters that are exported to the SPNA or Nordic Seas (Liu et al., 2019; Liu and Fedorov, 2021).

CHALLENGES AND OPPORTUNITIES

In the past decade, significant progress has been made in understanding Arctic-AMOC interactions. This understanding has been driven by observing and modeling advances such as the OSNAP array (Lozier et al., 2019), the Argo network (Jayne et al., 2017), new generations of coupled climate models (Fox-Kemper et al., 2019), very high-resolution ocean circulation models (Wang et al., 2018; Haine et al., 2021), and improved conceptual models that only include essential components of the Arctic and AMOC (Haine, 2021). The maturation of these capabilities and technologies are carrying us toward another phase of discovery.

For example, ocean models that are referred to as "eddy-resolving" (often using a spatial resolution of about 10 km) do not resolve the Arctic Ocean Rossby radius of deformation (1–15 km; Nurser and Bacon, 2014). Continuing improvements in computational capabilities (supercomputers), approaches (architectures), and algorithms (machine learning) are inevitably moving us toward ocean and climate models that will be able to resolve these critical scales in the next decade (Haine et al., 2021). This will allow us to resolve more of the small-scale processes critical for the large-scale Arctic Ocean and sea ice system and its connection to lower latitudes. It is hoped that the gradual move toward explicitly resolving more and more critical processes will reduce dependency on parameterizations as well as the biases that still plague representation of the Arctic in climate models. Important processes include exchanges between the extensive

Arctic shelves and the deep interior of the Arctic Ocean (as originally suggested by Aagaard et al., 1981), flow through narrow gateways like the CAA, and overflows (Fox-Kemper et al., 2019; Hewitt et al., 2022). Other processes will continue to require parameterizations into the foreseeable future, for instance, mixing (Fine et al., 2021) and brine rejection (Nguyen et al., 2009). Still, the agreement between freshwater fluxes modeled by the current generation of climate models and observations in Figure 5 is encouraging.

Another promising direction is the combination of models and observations. Data-assimilation approaches are being developed that allow ocean models to be initialized from states that more faithfully represent the real system, reducing biases. These approaches yield state estimates that use model dynamics to fill in data gaps to provide a consistent representation of the historical and current ocean and sea ice state (Schweiger et al., 2011; Nguyen et al., 2021).

Longer time series collected by existing monitoring arrays (Figure 5) will help us improve our understanding in the course of time, while observational methodologies are becoming more mature (Lee et al., 2019). Examples are Ice-Tethered Profilers, which are "upside-down" moorings that hang below the sea ice (Toole et al., 2011), and Argo floats that can avoid sea ice (see Lee et al., 2022, in this issue for a discussion of emerging technologies for ocean observing in the Arctic). All these developments are geared toward gaining a better understanding of the Arctic system and its interactions with the AMOC. Understanding these relationships and accurately modeling them are critical for predicting the future of the Arctic, the AMOC, and the rest of the climate system.

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SIDEBAR > GREENLAND ICE LOSS RATE

HOW THIS CENTURY COMPARES TO THE HOLOCENE

By Jason Briner

The Greenland Ice Sheet is melting at a devastating rate. Recent scientific reports like the Intergovernmental Panel on Climate Change Sixth Assessment Report (Fox-Kemper et al., 2021) highlight how vulnerable the Greenland Ice Sheet is to Arctic climate change, and they draw a dire picture of the impact of sea level rise around the globe.

In order to equip society with the best forecasts of sea level rise, scientists are constantly improving their ability to simulate—or model—ice sheet responses to climate change. Because ice sheet model simulations are simply numerical representations of future ice sheet change, a major emphasis of current research is reducing uncertainties in these predictions. Areas with large uncertainties include how atmospheric and oceanic forcing varies through time and the timescales (e.g., years, decades, centuries) at which each forcing can cause ice sheet change. Scientists have been observing ice sheet change for only a short period (decades), and knowledge of ice sheet responses to atmosphere and ocean changes that span longer time periods would greatly assist in reducing uncertainties.

One approach to improving knowledge of present and future ice sheet change is to study ice sheet changes from the geologic past. Briner et al. (2020) aimed to place contemporary and future elevated rates of Greenland ice loss in the context of Holocene—the past 12,000 years. The Holocene experienced a warmer-than-present time period that provides a partial analog for ongoing warming. The team concluded that Greenland Ice Sheet mass loss in this century will almost certainly be higher than in any century over the past 12,000 years (**Figure 1**).

The research team used a high-resolution ice sheet model driven by climate history generated from ice core data. The results were validated against geologic reconstructions (e.g., well-dated moraines) of past ice margin change. Because the ice sheet model was computationally intensive and the simulations were most robust where they could be validated with moraines (which mostly exist in southwestern Greenland), the study domain was limited to southwestern Greenland. Surface melting dominates Greenland ice mass change in southwestern Greenland, as opposed to dynamic discharge associated with marine glacier termini. Surface melt is simpler to model than dynamic discharge, so the simpler physics in the model for this region led to more trustworthy results.

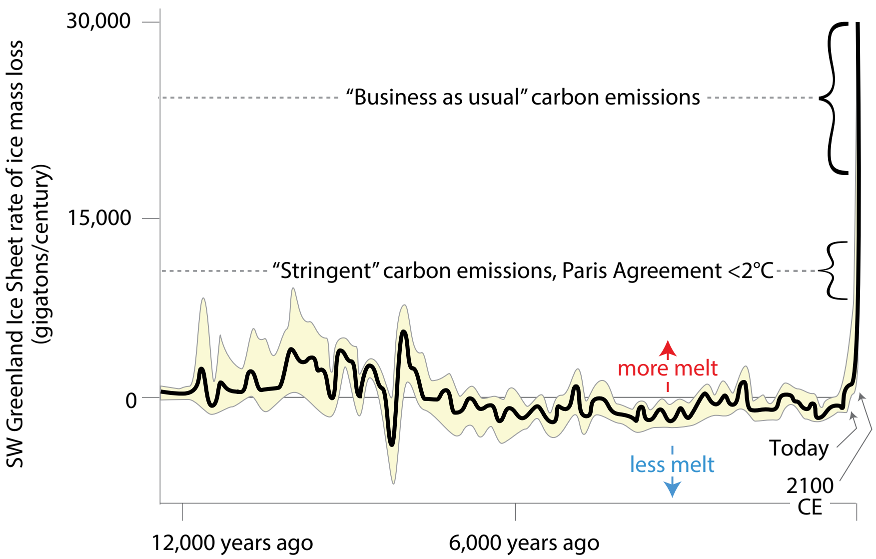

FIGURE 1. Rate of Greenland Ice Sheet mass loss simulated in every century from 12,000 years ago to 2100 CE. In future scenarios of Arctic warming, the Greenland Ice Sheet is predicted to melt at a higher rate than during the warmest centuries of the Holocene. The black line is the mean of an ensemble of nine ice sheet simulations, and the yellow shading shows the range of the nine simulations.

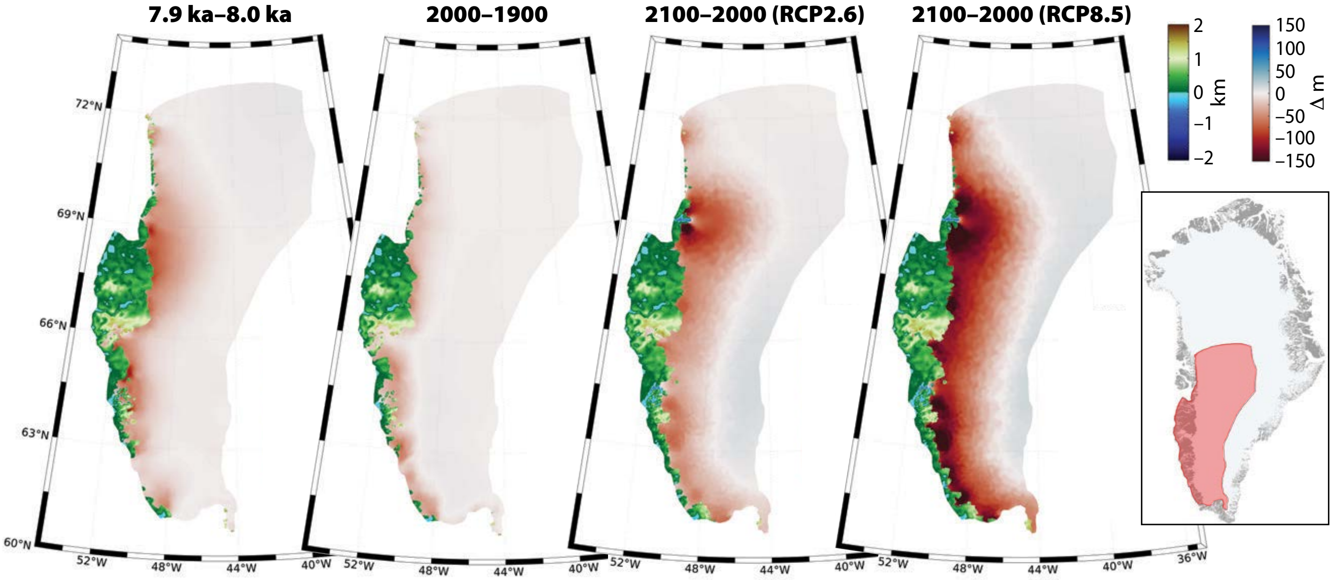

FIGURE 2. Numerical simulations of the change in surface elevation of southwestern Greenland Ice Sheet (meters per century), showing the warmest century in the Holocene (7.9–8.0 ka) compared to the twentieth century (2000–1900), and to projections of this century under RCP2.6 and RCP8.5 scenarios.

These results showed that the largest pre-industrial rates of ice mass loss (up to 6,000 gigatons/century) occurred in the early Holocene and were similar to the contemporary (CE2000–2018) rate of around 6,100 gigatons/century. Simulations of future mass loss from southwestern Greenland using the same model, based on Representative Concentration Pathway (RCP) scenarios corresponding to low (RCP2.6) and high (RCP8.5) greenhouse gas concentration trajectories, predict mass loss of between 8,800 and 35,900 gigatons over the twenty-first century. Comparison of the Briner et al. (2020) results with a recent Greenland Ice Sheet model intercomparison effort to assess twenty-first century ice mass loss (Goelzer et al., 2020) shows that the simulations are within, but at the lower end, of the model spread. These twenty-first century rates of ice mass loss exceed the highest rates over the past 12,000 years (Figure 2). Because rates of ice mass loss from the southwestern Greenland Ice Sheet scale linearly with the ice sheet as a whole, the results suggest that the rate of mass loss from the Greenland Ice Sheet this century will exceed the highest Holocene mass loss rates by a factor of about four. The amount of ice loss in southwestern Greenland this century would reverse the previous 4,000 years of cumulative ice growth.

The next steps of this research will allow simulation of the entire ice sheet at very high resolution, an endeavor that is becoming more and more computationally feasible. Improvements in simulating the complicated dynamics at the ice-ocean interface, where some of the most unstable parts of the ice sheet are located, are now ready to be included in new numerical simulations. These next stages will result in more robust estimates of the rate of ice mass change for both the past and the future Greenland Ice Sheet.

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HARMFUL ALGAL BLOOMS IN THE ALASKAN ARCTIC

AN EMERGING THREAT AS THE OCEAN WARMS

By Donald M. Anderson, Evangeline Fachon, Katherine Hubbard, Kathi A. Lefebvre, Peigen Lin, Robert Pickart, Mindy Richlen, Gay Sheffield, and Caroline Van Hemert

ABSTRACT. Harmful algal blooms (HABs) present an emerging threat to human and ecosystem health in the Alaskan Arctic. Two HAB toxins are of concern in the region: saxitoxins (STXs), a family of compounds produced by the dinoflagellate *Alexandrium catenella*, and domoic acid (DA), produced by multiple species in the diatom genus *Pseudo-nitzschia*. These potent neurotoxins cause paralytic and amnesic shellfish poisoning, respectively, in humans, and can accumulate in marine organisms through food web transfer, causing illness and mortality among a suite of wildlife species. With pronounced warming in the Arctic, along with enhanced transport of cells from southern waters, there is significant potential for more frequent and larger HABs of both types. STXs and DA have been detected in the tissues of a range of marine organisms in the region, many of which are important food resources for local residents. The unique nature of the Alaskan Arctic, including difficult logistical access, lack of response infrastructure, and reliance of coastal populations on the noncommercial acquisition of marine resources for nutritional, cultural, and economic well-being, poses urgent and significant challenges as this region warms and the potential for impacts from HABs expands.

Young male Pacific walrus resting on a beach, Chukchi Sea, Alaska. *Photo credit: Anthony Fischbach, US Geological Survey*

INTRODUCTION

The waters of the Alaskan Arctic (here defined as the interconnected US subregions of the northern Bering, Chukchi, and Beaufort Seas) are undergoing rapid and profound environmental and ecological changes due to substantial decreases in sea ice quality, extent, and duration as a result of atmospheric and ocean warming. Additionally, with a predominantly northward flow of water through the Bering Strait, alterations in southern and northern Bering Sea marine ecosystems are now propagating into the Chukchi Sea and beyond (Huntington et al., 2020), leading to cascading effects on marine ecosystems (Stevenson and Lauth, 2019). Among other warming-related impacts, harmful algal blooms (HABs) are emerging as a threat to marine-dependent species in the region, including humans. Although HAB species were first documented in the Alaskan Arctic as early as the mid-twentieth century (Bursa, 1963), new evidence suggests that their occurrence and future impacts may be much more widespread and severe than previously thought (Anderson et al., 2021a).

HABs are proliferations of algae that cause harm in a variety of ways, with a key mechanism being the production of potent toxins responsible for illness and death in humans and wildlife (Anderson et al., 2012). In the Alaskan Arctic, like elsewhere in the world, toxic algae directly enter the marine food web through planktivorous filter feeders, such as clams and zooplankton, and can accumulate to levels that sicken or kill higher trophic level consumers, including humans (Figure 1). Shellfish have historically been considered the primary source of dietary exposure for toxins, but a significant difference in the Alaskan Arctic is that coastal residents rely on a large diversity of marine resources for food, adding a new and poorly understood dimension to the threat from HABs.

There are two primary HAB toxins of concern in this region: (1) saxitoxin and its congeners (hereafter, STXs) produced by the dinoflagellate species *Alexandrium catenella*, and (2) domoic acid (DA) produced by some diatom species in the genus *Pseudo-nitzschia*. In many areas of the world, these toxins cause paralytic and amnesic shellfish poisoning (PSP and ASP, respectively) when shellfish are the toxin vectors, but both can also accumulate in other marine organisms through food web transfer (Figure 1). DAP is the term used to describe domoic acid poisoning among wildlife. Other HAB toxins are likely present within the region as well (e.g., diarrhetic shellfish toxins [DSTs] produced by *Dinophysis* spp.), but these are not presently viewed as significant threats.

Recently, STXs and DA have been detected in marine species throughout the Alaskan Arctic at a variety of trophic levels, including in benthic invertebrates, zooplankton, forage fish, seabirds, and marine mammals (Lefebvre et al., 2016; Van Hemert et al., 2021a). In most cases, reported concentrations in marine wildlife have been relatively low, but potential acute and chronic effects on wildlife health require further investigation. Likewise, there are no recent medical reports of impacts on human health, but the presence of HAB toxins across multiple trophic levels that serve as human food resources, combined with current and projected impacts of climate change (Anderson et al., 2021a), suggest a growing risk that warrants additional research and action.

Much of the Alaskan Arctic faces unique obstacles in monitoring and responding to HABs due to difficult logistical access and lack of response infrastructure. Besides concerns about food safety due to accumulation of toxins in marine organisms consumed by humans, HABs can impact food security by affecting fish and wildlife populations directly (i.e., causing illness or death among animals), further limiting access to these resources. The dearth of current knowledge about HABs in the Alaskan Arctic underscores the need for expanded research, monitoring, education, and communication to address food security, conservation, and public/wildlife health concerns. In this review, we summarize the primary HAB threats to the Alaskan Arctic, identify potential sources of exposure in the marine food web, and discuss implications for human and ecosystem health along with challenges to HAB monitoring and management in this dynamic and rapidly changing environment.

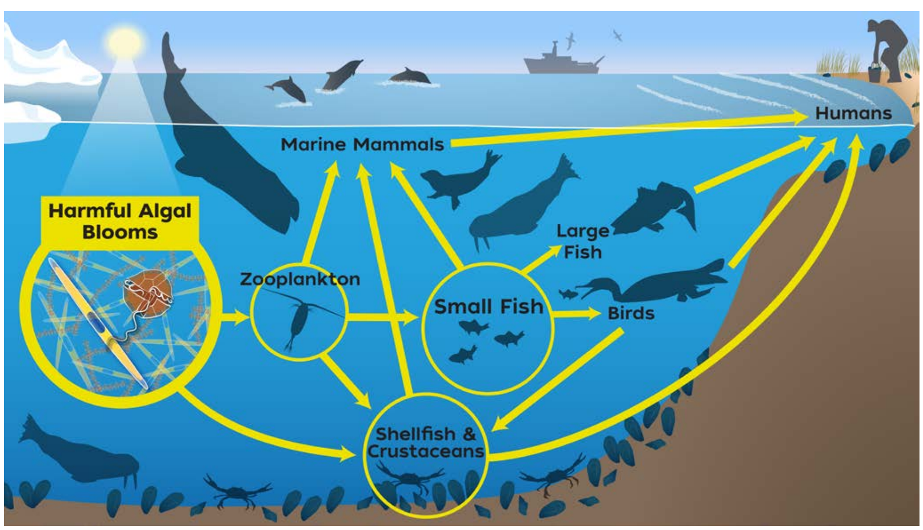

FIGURE 1. Toxins produced by harmful algal blooms (HABs) can be accumulated and transferred throughout the food web when algal cells are eaten by zooplankton, fish, and shellfish that are, in turn, consumed by other animals and humans. At sufficiently high levels, these toxins can sicken or kill both humans and wildlife. *Illustration created by Natalie Renier, WHOI Graphic Services*

ALEXANDRIUM AND STXs

Currently, the most significant threat to human and ecosystem health from HABs in the Alaskan Arctic is from *Alexandrium catenella,* a cyst-forming dinoflagellate that produces STXs. These toxins can accumulate in fish or shellfish to levels sufficient to cause illness and death in human consumers, as well as mortalities of marine mammals, birds, and fish. STXs have long been a problem in the Gulf of Alaska, with reports of illness and fatalities in southeastern and south-central Alaska dating back more than 200 years (Lewitus et al., 2012). In contrast, there are few documented reports in the Alaskan Arctic, though Indigenous oral history cited by Fair and Ningeulook (1995) describe "a red tide at one time which caused many deaths" at Ipnauraq (located in the US Bering Strait region), though no details were provided on the food consumed, symptomatology, or when this occurred.

Alexandrium catenella has a unique multi-stage, meroplanktonic life cycle that allows it to survive unfavorable conditions in seafloor sediments and bloom seasonally in surface waters. While planktonic blooms and shellfish toxicity are predominantly caused by vegetative (swimming, photosynthetic) cells, this species also produces a resting cyst that lies inactive on or near the seafloor and germinates when temperatures and other conditions are favorable. The distribution and density of resting cysts are used to predict the location and timing of future bloom occurrences in some regions, such as the Gulf of Maine (Anderson et al., 2014). *Alexandrium* blooms generally occur in the spring at temperate latitudes but appear to be present in the late summer and into early fall in the Arctic (Anderson et al., 2021a).

In coastal regions north of the Bering Strait, observations of *A. catenella* are limited to a few sporadic reports over many years, and blooms have historically not been a significant food safety concern. However, changing environmental conditions driven by warming ocean temperatures are providing an increasingly hospitable environment for *A. catenella* growth and persistence.

Multiple observations by several research groups over the past decade have provided clear evidence of widespread and dense *Alexandrium* cyst and cell concentrations in the Alaskan Arctic, indicating the potential for significant bloom development in waters where temperatures were formerly unfavorable. Gu et al. (2013) were the first to identify *A. catenella* in the US portion of the Chukchi Sea (hereafter simply termed "Chukchi Sea") and report the toxicity of several isolates. Natsuike et al. (2013, 2017) subsequently reported high concentrations of *A. catenella* resting cysts in sediments on the Chukchi shelf, as well as bloom populations in the water column, and suggested that the cells were transported northward from the northern Bering Sea. Recently, extremely high concentrations of *Alexandrium* cysts and vegetative cells were documented over large areas in the Chukchi Sea and adjacent waters, and over multiple sampling years (Anderson et al., 2021a). These surveys reveal a massive and persistent cyst accumulation zone (cystbed) on the seafloor of the Chukchi Sea, extending westward to (and presumably beyond) the maritime border between the United States and the Russian Federation (Figure 2). Maximum cyst concentrations in this cystbed are among the highest reported for this species globally. Bloom populations of *A. catenella* documented in surface waters of the Bering Strait and the Chukchi Sea were also notable, with dangerously high cell concentrations covering very large areas. As with the Chukchi Sea cystbed, these planktonic blooms were certainly more widespread than were sampled, extending an unknown distance into Russian waters where sampling was not possible. The *A. catenella* cystbed in the Chukchi Sea is the largest in extent and overall abundance globally. It is at least six times larger in area and 15 times greater in cyst abundance compared to a similar feature in the Gulf of

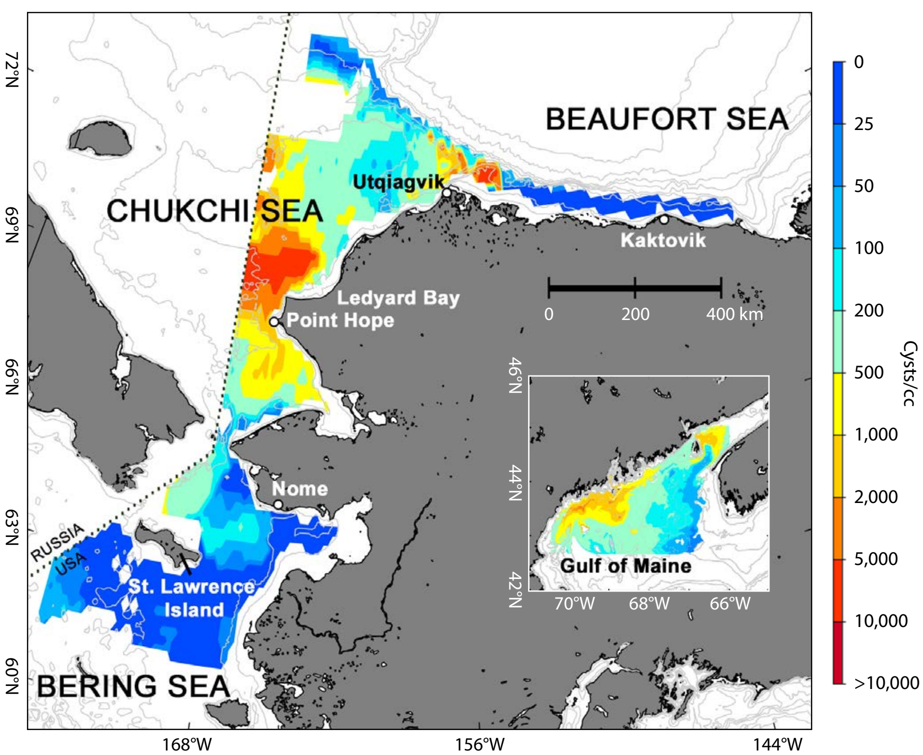

FIGURE 2. Alaskan (2018–2020) and Gulf of Maine (2004–2012) *Alexandrium catenella* cyst abundance in surface sediments, depicted on the same scale (Albers Equal-Area Conic projection). Sites visited across multiple years were averaged to create these composite maps.

Maine (Figure 2 inset) that sustains large-scale, annually recurrent, and dangerous blooms (Anderson et al., 2014). The same now seems likely in the Alaskan Arctic.

The origins and development of these Arctic blooms as well as the formation and persistence of the regional cystbed can be attributed to two mechanisms (Anderson et al., 2021a). The first involves northward transport of *A. catenella* populations through the Bering Strait into the Chukchi Sea from established blooms in US and Russian waters to the south (Figure 3a), as originally proposed by Natsuike et al. (2017). North of Cape Lisburne on the Chukchi Sea shelf, the poleward flow weakens due to the gentler bottom slope, allowing cysts to settle and accumulate; a similar mechanism occurs on the Alaskan Beaufort Sea shelf just east of Point Barrow where another cystbed is located (Anderson et al., 2021a). Over many years, this slowing of the circulation, coupled with episodic advection of southern blooms with resulting cyst production and deposition, has created a regional cystbed of unprecedented size and density. Importantly, historic ocean seafloor temperatures in this cystbed region were likely too cold to support significant cyst germination, with most cysts cycling repeatedly between dormancy (alive but unable to germinate) and quiescence (able to germinate but waiting for favorable conditions) (Fischer et al., 2018). In this scenario, most cysts would remain in the seafloor sediments, unable to germinate and become active because of cold temperatures, with repeated deposition events from transported blooms exceeding small germination losses (Figure 3b). *Alexandrium* can survive as a cyst for a century or more (Miyazono et al., 2012) until conditions are appropriate for growth. This imbalance between inputs and losses and the longevity of cysts may explain the extraordinary size and density of the Alaskan *A. catenella* cystbed.

Historically, the main threat to wildlife and human health from STXs was from episodic, advected blooms in the waters overlying the "sleeping giant" Chukchi Sea cystbed (Figure 2; Anderson et al., 2021a). Now, however, rapid warming of the bottom waters of the Chukchi shelf has exceeded the temperature threshold above which substantial cyst germination and vegetative cell growth can occur. The warming is due to increased heat flux through the Bering Strait, which is driven by the greater heat content of northern Bering shelf waters, together with enhanced northward volume transport. The former is due to stronger atmospheric heating, and the latter results from a larger sea level height difference between the Pacific and the Arctic.

This changing thermal regime favors a second mechanism of bloom development: local bloom initiation from the Alaskan Arctic cystbed (Figure 3c).

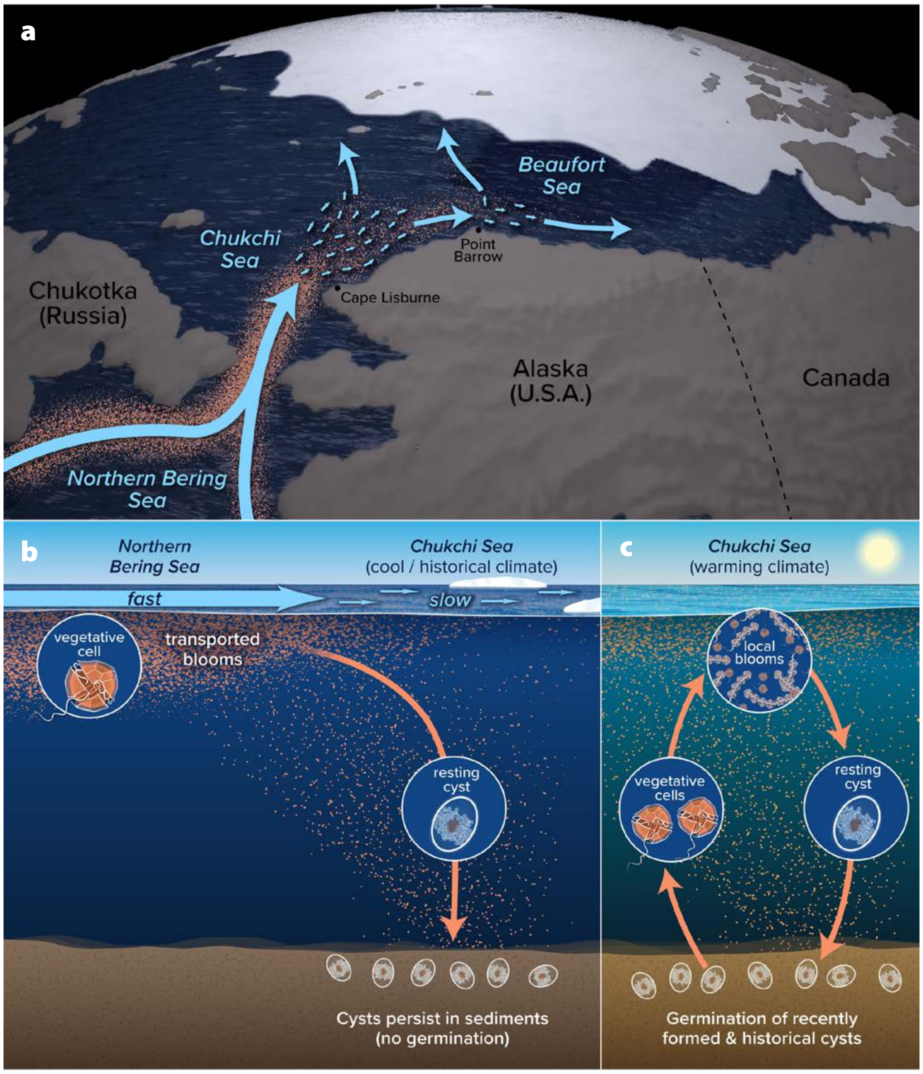

FIGURE 3. Schematic diagrams of *Alexandrium catenella* bloom dynamics in the Alaskan Arctic region. Panel (a) depicts the transport of blooms (orange dots) from the northern Bering Sea into the Chukchi Sea and beyond. North of Cape Lisburne and again east of Point Barrow, flow speeds decrease (represented by the smaller arrows), allowing *Alexandrium* cysts to be deposited (b). Panels (b) and (c) show two scenarios for bloom and cyst dynamics. (b) Bottom waters were historically too cold to promote germination of cysts, which presumably cycled repeatedly through dormancy and quiescence. Meanwhile, continued deposition of new cysts occurred via blooms transported from the south. Such sustained inputs led to extremely dense cyst concentrations and a large cystbed. (c) With warmer bottom water temperatures, cysts are able to germinate and initiate local blooms that in turn deposit new cysts to sustain the process. These locally formed cysts are supplemented with those produced by transported blooms, again leading to large and dense cystbeds. *Graphics created by Natalie Renier, WHOI Graphic Services*

Anderson et al. (2021a) estimate that the approximately 2°–4°C increase in bottom water temperatures in the Chukchi Sea over the past two decades has likely increased cyst germination flux twofold and advanced the timing of cell inoculation into the euphotic zone by 20 days. Furthermore, warming of surface waters supports more rapid cell division and bloom development, as well as prolonged bloom duration. Together, these complementary mechanisms of bloom development in the region, along with continued warming, dramatically enhance the potential for large-scale, self-initiating, and annually recurrent blooms, with more intense and widespread HAB impacts.

PSEUDO-NITZSCHIA AND DA

In recent decades, DA produced by the pennate diatom genus *Pseudo-nitzschia* has emerged as a serious threat in coastal waters of North America, causing ASP and DAP events and fisheries closures on the Atlantic, Pacific, and Gulf of Mexico coasts and across a wide range of latitudes (Anderson et al., 2021b). While the Alaskan Arctic has not experienced DA events at the magnitude observed at lower latitudes, the presence of DA in Arctic phytoplankton and macrofauna points to an emerging threat (Lefebvre et al., 2016; Huntington et al., 2020). With *Pseudo-nitzschia* blooms and DA production linked in part to anomalously warm ocean conditions in the northeast Pacific (McKibben et al., 2017), such as warm phases of the Pacific Decadal Oscillation and the Oceanic Niño Index, more severe DA events could occur due to Arctic warming.

With over 50 described *Pseudo-nitzschia* species, this genus occupies a wide range of temperature and salinity regimes, from estuarine to open-ocean to sea ice (reviewed by Bates et al., 2018). Approximately half these species produce DA, but to varying degrees. Cryptic morphological diversity among *Pseudo-nitzschia* species further complicates efforts to monitor and understand the ecological conditions that result in DA production. Data on the diversity and distribution of *Pseudo-nitzschia* assemblages in the Alaskan Arctic are limited, but at least six species of predominantly polar, subpolar, or temperate origin have been reported, many of which occur in sea ice (Figure 4; Poulin et al., 2011; Percopo et al., 2016). Several produce DA in culture, including *P. seriata* and *P. obtusa,* although few Arctic strains have been cultivated and tested (Bates et al., 2018; Weber et al., 2021).

For toxic species, biological, chemical, and physical factors such as temperature, light, nutrient availability, sexual reproduction cycles, and the presence of grazers can influence DA production (Bates et al., 2018). Arctic isolates of *P. obtusa* and *P. seriata* increased DA production after exposure to copepods: *P. seriata* increased production by 3300% and toxicity was induced in *P. obtusa,* previously considered non-toxic (Harðardóttir et al., 2015). This was most likely a chemically mediated reaction, because DA production in *P. seriata* also increased following exposure to copepod exudates (Tammilehto et al., 2015). These findings suggest that co-abundance of *Pseudo-nitzschia* species and zooplankton (which also concentrate DA), in addition to other factors, should be considered when evaluating DA toxicity in the Alaskan Arctic.

The majority of DA observations in the region are associated with marine wildlife rather than plankton, but recently, toxin production by plankton assemblages has been observed. During the summers of 2017 and 2018, DA was detected in seawater collected from the northern Bering Sea, Bering Strait, Chukchi Sea, and Beaufort Sea (Huntington et al., 2020; recent work of author Hubbard and colleagues), suggestive of broad regional distribution of toxic species. Particulate concentrations of DA measured in the Alaskan Arctic were generally low (<311 ng L^{-1}; Huntington et al., 2020) compared to the high levels (15,000 ng L^{-1}) that can occur in the US Pacific Northwest (McCabe et al., 2016), a region with recurring DAP events that is connected to the Alaskan Arctic by major current systems. Duration of blooms in the region is currently unknown (and a bloom threshold has yet to be operationally defined for the

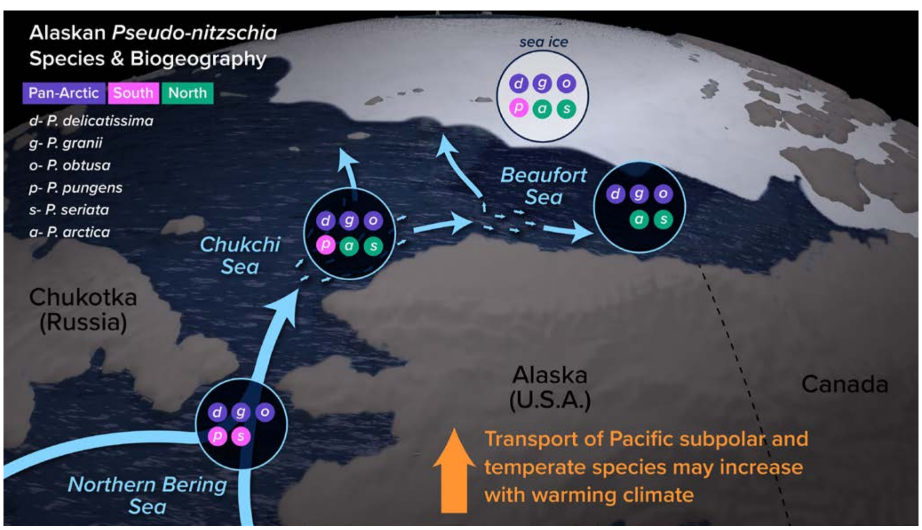

FIGURE 4. Distribution of *Pseudo-nitzschia* species reported to occur in the Alaskan Arctic (Bering Sea, Chukchi Sea, Beaufort Sea, and sea ice; Bates et al., 2018; recent work of author Hubbard and colleagues). Species are color-coded based on biogeography in the Alaskan Arctic, including distribution across all subregions shown (Pan-Arctic), those suspected to have a more southern origin (in pink), and those suspected to have a more northern origin (in green). Specific locations were not referenced for *P. pseudodelicatissima,* which may have been confounded with the recently described *P. arctica* (Percopo et al., 2016). For *P. seriata,* two genetically distinct populations are shown: one previously observed in temperate Pacific waters, and one observed in Atlantic Arctic waters. *Illustration created by Natalie Renier, WHOI Graphic Services*

Alaskan Arctic), but the persistence of cells in sea ice and limited observations from seawater samples, as well as DA in biota, suggest that *Pseudo-nitzschia* is likely present year-round.

In other regions, *Pseudo-nitzschia* species composition, abundance, and DA concentrations are known to change rapidly over time and space due to ocean currents and changing ecological conditions. This is the case in the Alaskan Arctic as well, where varied water masses and dynamic circulation are important determinants in the distribution of *Pseudo-nitzschia* spp. and zooplankton grazers over short and long timescales. Indeed, a diversity of species occur across the region and over seasons, including in sea ice (Poulin et al., 2011; Bates et al., 2018). Given the warming temperatures of Pacific-origin water entering the Arctic through the Bering Strait, together with the increased flux of this water, there is the potential for northward expansion of more temperate and subpolar *Pseudo-nitzschia* species (Figure 4). Predicted changes in hydrographic regimes and sea ice extent/duration, coupled with complex and environmentally dependent mechanisms underlying growth and DA production, suggest that multiple factors are likely to be important for toxicity over varying timescales.

Although there is still much to be learned about the potential risk to human communities and wildlife populations in the Alaskan Arctic from this important HAB group, the presence of toxic *Pseudo-nitzschia* species indicates potential for trophic transfer through Alaskan food webs. Fortunately, DA levels detected thus far in water and wildlife (see below) have been low, but certainly warrant continued research and monitoring. The potential effect of DA on Arctic ecosystems is a major concern, though not enough is known of lethal doses and toxin transfer pathways to be definitive at this time. Likewise, predicting what projected ocean warming will do to distribution and abundance of toxigenic *Pseudo-nitzschia* species is challenging.

HUMAN AND WILDLIFE HEALTH IMPLICATIONS OF STXs AND DA

During toxic HAB events, STXs and DA accumulate in filter-feeding marine organisms such as zooplankton, clams, worms, and fish. These accumulated toxins can be passed to upper trophic levels, where they can cause severe illness and death of humans and wildlife (Figure 1; Landsberg et al., 2014). Although both STXs and DA are detected throughout food webs in many parts of the world, their known impacts vary by taxa and geographic region. Globally, STXs have been responsible for mortality in fish, invertebrates, sea turtles, seabirds, and marine mammals (Landsberg et al., 2014). In contrast, reports of DA-associated wildlife mortality have been limited to marine mammals and seabirds, mostly along the west coast of the contiguous United States (Landsberg et al., 2014). Both STX- and DA-producing HABs are present in Alaskan Arctic ecosystems and have the potential to impact a wide variety of wildlife species, as well as humans. Although no confirmed cases of STXs- or DA-associated poisonings have yet been reported in wildlife or humans in the Alaskan Arctic, these toxins have been documented in zooplankton, clams, worms, planktivorous fish, marine mammals, and seabirds, providing evidence of exposure to HAB toxins across multiple trophic levels (Lefebvre et al., 2016; Van Hemert et al., 2021a; Lefebvre et al., 2022; Figure 5).

Typically, STXs and DA are found at highest concentrations in gastrointestinal tracts, livers, and kidneys of marine organisms, a pattern that has also been observed among Arctic seabirds and marine mammals (Lefebvre et al., 2016; Van Hemert et al. 2021a). Planktivorous fish have also been shown to depurate toxins quickly and have the highest concentrations (>90%) in viscera (Lefebvre et al., 2001). However, some species of clams, like the razor clam (*Siliqua patula*), have been shown to contain DA in edible tissues at levels above regulatory limits and to remain toxic for over a year (Wekell 1994). More species-specific information on uptake and depuration is needed to determine which tissues could harbor potentially harmful

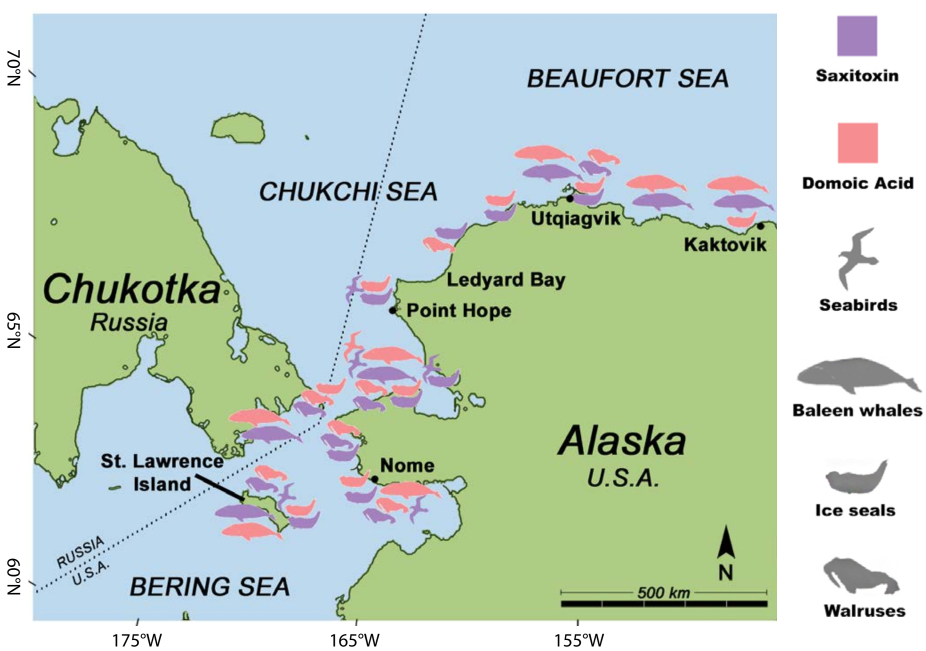

FIGURE 5. Map of locations where stranded or subsistence harvested marine mammals and seabirds have tested positive for saxitoxin (STX, purple) and/or domoic acid (DA, red) in samples collected from St. Lawrence Island to the Beaufort Sea from 2001 to 2021. Taxa include seabirds, baleen whales, ice seals, and walrus. Algal toxin detection limits for wildlife samples were approximately 4 ng DA/g for domoic acid and 3 ng STX eq./g for saxitoxin (Lefebvre et al., 2016).

levels of toxins and whether human risk reduction is possible through specific harvesting or food preparation measures.

Based on available food web data from the Alaskan Arctic, STXs appear to be a more urgent threat to wildlife and human health than DA. Across multiple taxa, STXs have been detected more frequently and at higher relative concentrations than DA (Lefebvre et al., 2016; Van Hemert et al., 2021a). DA levels measured in zooplankton, clams, worms, fish, and marine mammals from the Chukchi Sea and Alaskan Beaufort Sea regions were well below the seafood safety regulatory limit (20 µg DA/g tissue; author Lefebvre, unpublished data). In contrast, concentrations of STXs at or near the seafood safety regulatory limit (80 µg STX eq./100 g tissue) were measured in Alaskan Arctic clams, zooplankton, and Pacific walruses (Lefebvre et al., 2022).

The higher levels of STXs found in clams make them the most toxic vectors identified in the Alaskan Arctic region to date, suggesting that they present a distinct risk to marine mammals and humans. This finding agrees with previous studies showing higher prevalence and concentrations of STXs in clam-feeding walruses and bearded seals compared to other marine wildlife that feed on fish or zooplankton, such as spotted seals, bowhead whales, and seabirds (Lefebvre et al., 2016; Hendrix et al., 2021; Van Hemert et al., 2021a; Lefebvre et al., 2022).

In addition to known shellfish vectors, other potential sources of STXs and DA in Arctic food webs warrant consideration. Forage fish are known to accumulate STXs in regions where *A. catenella* blooms are common, including the Gulf of Alaska (Van Hemert, 2021b). In a 2019 survey of Arctic forage fish, STXs were detected at low to moderate concentrations in fish collected from the northern Bering Sea and Bering Strait region, but not in fish collected from the northern Chukchi and Alaskan Beaufort Seas (Lefebvre et al., 2022). More samples are clearly needed to determine the role of fish as potential vectors in the Alaskan Arctic.

Nontraditional vectors (Deeds et al., 2008) include zooplankton and other marine invertebrates that are important food sources for many wildlife species in the Arctic. The high energetic demands of northern seabirds, whales, and other cold-adapted taxa may result in the consumption of harmful quantities of toxin during HAB events, even when prey toxin concentrations are relatively low (Van Hemert, 2021b). It is also important to note that toxic doses and susceptibility among marine mammals and seabirds have not yet been determined, and impacts on wildlife health cannot be inferred from human seafood safety guidelines (Lefebvre et al., 2016; Van Hemert et al., 2021a). As knowledge of HABs in the Alaskan Arctic expands, additional sampling as well as targeted experimental studies are needed to determine species' sensitivity to better understand risks to piscivorous seabirds and other marine wildlife.

Although many questions remain about the ecosystem-level impacts of HABs in the Alaskan Arctic, growing evidence indicates the possibility of an emerging wildlife health issue. Recent reports demonstrated increasing prevalence of DA in marine mammals (Hendrix et al., 2021), along with possibly harmful concentrations of STXs in seabirds associated with known mortality events (Van Hemert et al., 2021a). These findings, combined with projections of more frequent and intense STX-producing HABs due to warming ocean conditions in the Arctic (Anderson et al., 2021a), suggest that marine wildlife (and the people who harvest and consume them) may face growing exposure risks.

The potential impacts of HABs on the food web of the Alaskan Arctic are far-reaching, as marine wildlife of the northern Bering, Chukchi, and Beaufort Seas are essential to the nutritional, cultural, and economic well-being of coastal communities. HAB toxins present two major hazards to coastal communities: (1) illness or mortality via direct consumption of potentially toxic seafoods, and (2) compromised food security via both avoidance of foods due to fear of toxicity and the loss (through mortality) of essential marine resources used for food. Of note are recent studies demonstrating that repetitive, low-level exposure, especially in subsistence populations and high fish/shellfish consumers, can have negative outcomes (e.g., problems with everyday memory; e.g., Grattan et al., 2018).

It is essential to recognize not only the acute toxicity risks posed by HABs but also the multifaceted impacts on traditional food sources and culture. The low-level presence of STXs and DA is not new to northern and western Alaskan waters (Lefebvre et al., 2016), but local concerns now reflect both a rapid increase in knowledge about HABs as well as the associated shift in perceptions of food safety and availability.

CHALLENGES AND APPROACHES TO MONITORING AND MANAGEMENT

The Alaskan Arctic faces multiple challenges in monitoring and responding to HABs, some of which are unique to the region. A detailed analysis is beyond the scope of this review; here, we summarize the main challenges and suggest possible approaches.

Efforts to monitor and manage HABs in the region are hindered by a lack of information, limited infrastructure, and unique spatial challenges inherent in Alaskan land- and seascapes (Figure 6). Foremost among the challenges is the need to provide coverage across large stretches of sparsely populated coastline. Transportation and communication infrastructure is limited and often impacted by harsh weather. As a first step toward enhanced communication, the Alaska Harmful Algal Bloom Network (AHAB: https://aoos.org/alaska-hab-network/) has been established to share information among a diverse group of scientists and interested stakeholders throughout Alaska (Anderson et al., 2019). This stakeholder-initiated effort is currently funded by federal appropriations that are subject to funding uncertainties, and thus a more stable state-supported communications strategy and network might be needed to enhance and sustain HAB response.

Scientists, managers, and agencies concerned with HAB events are primarily urban-based in Alaska, far from the northern and western coasts, so they are largely reliant on coastal communities for awareness of a HAB event or human medical emergency. The lack of a robust infrastructure contributes to a high-risk situation, as recently demonstrated in 2020 with the first human HAB/PSP fatality since 2010 in Alaska, and the first reported fatality in western Alaska (Alaska DHSS, 2020).

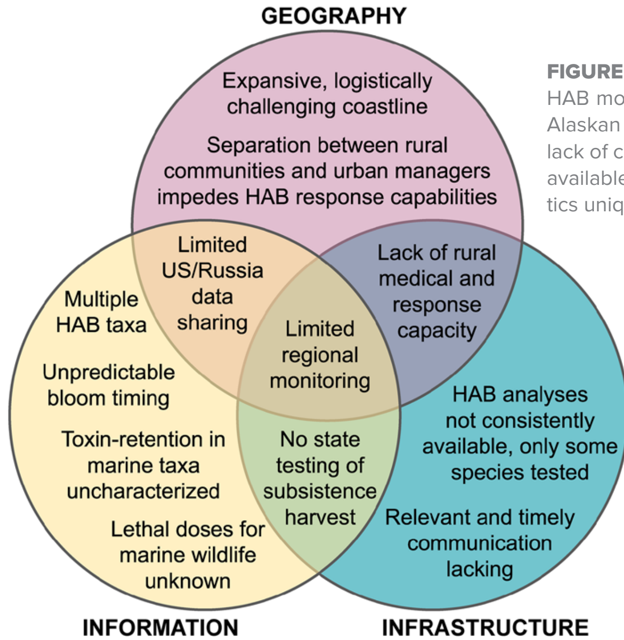

FIGURE 6. Overview of challenges to HAB monitoring and management in the Alaskan Arctic. Challenges derive from lack of complete information, limitation of available infrastructure, and spatial logistics unique to Alaskan geography.

An additional complication is that resource managers, community leaders, and regulatory officials must deal with multiple HAB toxins and algal species that occur in different seasons and locations, with blooms that are highly episodic and as yet unpredictable. HAB toxins can also accumulate in, and affect, a diverse suite of marine species that are food sources for local communities. The State of Alaska tests all commercial shellfish harvested, but there is no state-run testing program for the recreational and subsistence harvest. With no federally authorized commercial harvest of seafood in the Chukchi and Beaufort Seas, all seafood is harvested on a noncommercial basis and thus is not included in state-funded HAB monitoring.

Given the geographic and logistical constraints of monitoring HABs in the Alaskan Arctic and the lack of a state-funded toxin testing program for noncommercial harvest, the marine ecosystems of the Alaskan Arctic, and the people who rely on them, are at risk. A monitoring approach to be considered would be the establishment of a local or regional monitoring program, perhaps modeled after the program run by the Sitka Tribe of Alaska. This effort is focused on the Gulf of Alaska and is limited to shellfish, but staff and facilities for HAB toxin analysis are in place to serve community concerns about HABs through shellfish toxin testing, paid for by the users. Currently, there is no community-based HAB testing program in the Alaskan Arctic, and if one is established, it is important to recognize that shellfish are only a minor and occasional component of diets in the region. Regional monitoring programs will thus need to develop protocols and capabilities to test seabirds, fish, and marine mammals as well. Ongoing research by university, agency, and other partners can provide information about the presence of HAB toxins in fish and wildlife, but current sampling efforts are limited, and many diagnostic tools used are not directly applicable to food safety assessments.

Experiences in other regions of the world suggest that a plankton screening program to detect HAB cells in coastal waters could also be a useful element in local or regional monitoring programs. Local monitoring using plankton nets and inexpensive microscopes is common in many areas subject to HABs (Trainer et al., 2014), and training and funding to establish this capability should be a high priority activity in the Alaskan Arctic going forward. Given the many existing and growing challenges to coastal communities, however, citizen or volunteer plankton monitoring programs may not be feasible in this region. The direct testing of seafood harvest should therefore be considered, though the manner in which this could be accomplished is unclear given limited transportation infrastructure and analytical capabilities.

With respect to ecosystem health and food security, potential impacts from STXs and DA to most marine wildlife in the Alaskan Arctic are unknown and thus there is no firm guidance to provide for the safety of coastal communities. Ongoing grant-funded research programs will soon provide data of this type, and it will be critical to include effective communication and outreach plans to provide coastal communities the data and implications as they become available.

Yet another concern is that the marine ecosystems of the Alaskan Arctic are shared with the Russian Federation, and transboundary communications can be logistically, politically, and bureaucratically challenging. Efforts are needed to promote collaborations in research, monitoring, and communications to protect shared wildlife resources and public health.

Recent technological advances in HAB monitoring may also provide important monitoring tools for the region. Given frequent cloud cover and the lack of HABs of sufficient density to be visible from space, traditional satellite remote sensing has limited utility in the Arctic.

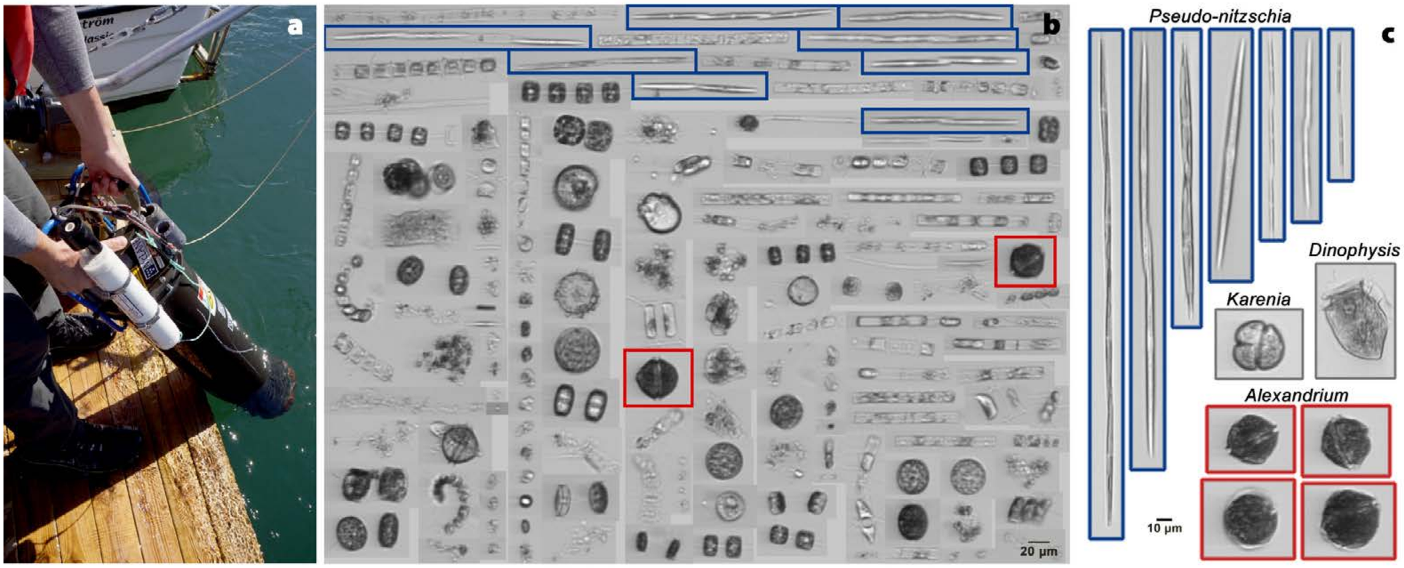

FIGURE 7. (a) An Imaging FlowCytobot (IFCB). *Image credit: Michael Brosnahan, WHOI* (b) Examples of phytoplankton imaging data that the instrument produces. A single water sample collected from shipboard underway seawater in the Chukchi Sea during an August 2018 cruise contained *Alexandrium* (red boxes) and *Pseudo-nitzschia* (blue boxes). (c) Post-processing of IFCB imagery classifies cells by type, allowing easy identification and quantification of HAB cells, including *Alexandrium, Pseudo-nitzschia*, *Karenia*, and *Dinophysis.*

Of more value are new sensors capable of detecting and quantifying HAB cells and toxins in situ (Doucette and Kudela, 2017). A promising development in this regard is the advent of ocean observing systems—arrays of moored and mobile instruments that can collect and transmit data continuously from remote locations to shore-based scientists and managers. Instruments capable of measuring HAB cells and/or toxins already exist, such as the Imaging Flow Cytobot (IFCB), a high-speed, submersible microscope that can autonomously operate 24/7 and take hundreds of thousands of images of phytoplankton daily (Olson and Sosik, 2007). Machine-learning algorithms then identify and enumerate algal species such as the major HAB taxa described here, providing near-real-time data on HAB threats (Brosnahan et al., 2015). These instruments can be deployed on docks or piers or placed on fishing or research vessels for analysis of underway samples (Figure 7). It should also soon be possible to deploy them seasonally on autonomous surface vehicles (ASVs) equipped with solar power and communications hardware. Given the demonstrated northward transport of *Alexandrium* blooms through the Bering Strait and into the Chukchi Sea, an IFCB-equipped ASV located near Kotzebue Sound could provide valuable data on incoming HABs, for example.

These are some of the approaches that could be taken to begin to monitor for and respond to HAB events in the Alaskan Arctic. Many other regions of the world face recurrent HABs that contaminate seafood products and affect ecosystem health, yet it has proven possible to protect human health and sustain fisheries and other ecosystem services through informed management actions. The unique nature of the Alaskan Arctic, the lack of scientific understanding of HAB impacts on marine wildlife, and the reliance of coastal populations on noncommercial harvesting for nutritional, cultural, and economic well-being poses new and significant challenges that need to be immediately addressed as this region continues to warm and the potential impacts from HABs expand.

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SIDEBAR > OBSERVATIONS OF DECLINING PRIMARY PRODUCTIVITY IN THE WESTERN BERING STRAIT

By Karen E. Frey, Jaclyn Clement Kinney, Larry V. Stock, and Robert Osinski

The shallow (~50 m deep), narrow (~85 km wide) Bering Strait is the sole marine link between the Pacific and Arctic Oceans and represents a critical northward throughflow of freshwater, nutrients, and heat into Arctic waters from lower latitudes (Woodgate and Peralta-Ferriz, 2021). Three water masses enter the Chukchi Sea through the Bering Strait from the Pacific: Anadyr Water (AW), Bering Shelf Water (BSW), and Alaskan Coastal Water (ACW) (Coachman et al., 1975). The western Bering Strait in particular has long been known to be a region of consistently high primary productivity throughout the spring and summer open-water season (Sambrotto et al., 1984; Springer and McRoy, 1993; Brown et al., 2011). This productivity is sustained through the delivery of high-nutrient AW waters via the northern branch of the bifurcated Bering Slope Current (Clement Kinney et al., 2009, 2022; Lowry et al., 2015; Pickart et al., 2016) that also causes the Chukchi Sea to the north to be one of the most productive shelves in the Arctic (Hill et al., 2018). Western Bering Strait waters are clearly differentiated from lower productivity waters observed in the eastern Bering Strait that are characterized by relatively low-nutrient, freshwater-dominated ACW (Woodgate and Aagaard, 2005; Lee et al., 2007). However, time series of satellite observations over the last two decades have revealed statistically significant early season (June) declining trends in chlorophyll-*a* concentrations and primary productivity in the western Bering Strait. In particular, June chlorophyll-*a* concentrations have declined by ~58%, and June primary productivity has declined by ~34% over the 2003–2020 period. These declining trends appear to be associated with reductions in sea ice cover and increases in primary production upstream in the Gulf of Anadyr during May, with potential implications for decreased nutrient availability downstream in the western Bering Strait during June.

To investigate recent biological change in the Bering Strait, we compiled a satellite-based time series of chlorophyll-*a* concentrations derived from Aqua-Moderate Resolution Imaging Spectroradiometer (Aqua-MODIS) calibrated radiances using two algorithms: the OC3m algorithm that was developed at NASA Goddard Space Flight Center (GSFC) and makes use of band ratios and in situ measurements (O'Reilly et al., 1998) and the CI algorithm that makes use of reflectance differences in conjunction with a model (Hu et al., 2012). The data are made available by the Ocean Biology Processing Group and were downloaded from the GSFC Distributed Active Archive Center (DAAC) at https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Daily/4km/chlor_a/. Chlorophyll-*a* concentration data were also combined with sea surface temperature data and additional data sets to derive net primary productivity using a broadly utilized algorithm (Behrenfeld and Falkowski, 1997) that has previously been employed to report changes across the Arctic region (Frey et al., 2021). Monthly chlorophyll-*a* and primary productivity data were only utilized where sea ice concentrations were <10% and were otherwise reported as missing data. For further context, we investigated sea ice concentration data obtained from the Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) passive microwave instruments, calculated using the Goddard Bootstrap (SB2) algorithm (Comiso et al., 2017a,b). Modeled surface nitrate concentrations were obtained from the Regional Arctic System Model (RASM; e.g., Clement Kinney et al., 2020). For all data sets (chlorophyll-*a*, primary productivity, sea ice, and surface nitrate), monthly time series were compiled for May and June, and the Theil-Sen median decadal trends for each month (2003–2020) were calculated, with statistically significant ($p < 0.1$) trends identified using the non-parametric Mann-Kendall test for monotonic trend (Mann, 1945; Kendall, 1975). The Theil-Sen median trend uses a robust non-parametric trend operator that is particularly well suited for assessing the rate of change in noisy and/or short time series (Hoaglin et al., 2000), which in this study is 18 years. For those data sets that include missing data (chlorophyll-*a* and primary productivity), we show only those trends for pixels that had at least 71% of the time series present (or in the case of this study, 13 of the 18 time steps). This requirement ensures that only robust trends are reported, given that the "breakdown bound" for the Theil-Sen trend is 29% (meaning that unknown or potentially "wild" values would have to persist for more than 29% of a time series in order to affect the overall trend values; Hoaglin et al., 2000).

Increasing trends in marine primary productivity across the Arctic owing to shifts in sea ice cover, seawater temperatures, and nutrient availability have been widely reported (Arrigo et al., 2008; Pabi et al., 2008; Arrigo and van Dijken, 2015; Clement Kinney et al., 2020; Lewis et al., 2020; Frey et al., 2021). In contrast to those reports of large-scale increases in primary productivity, **Figure 1** identifies an important and unusual regional location of early season (June) declines in productivity, with potential implications for nutrient and carbon delivery downstream (northward) across the Chukchi Sea shelf. During May (over the 2003–2020 period), we observe strong declines in sea ice concentration in the Gulf of Anadyr

(Figure 1a) with increases in surface nitrate concentrations (Figure 1c), and these are in turn associated with increasing trends in both chlorophyll-*a* (Figure 1e) and primary productivity (Figure 1g). However, during June, we observe (and model with RASM, not shown) strikingly strong and spatially cohesive declines in chlorophyll-*a* (Figure 1f) and primary productivity (Figure 1h) downstream of the Gulf of Anadyr in the western Bering Strait along the coast of the Chukotka Peninsula. By June, sea ice has typically already exhibited seasonal breakup in the Bering Strait region (Frey et al., 2015), and we see no trends in sea ice cover in the western Bering Strait (Figure 1b). Significant declining trends in June surface nitrate concentrations (Figure 1d) geographically mirror the observed declines in chlorophyll-*a* (Figure 1f) and primary productivity (Figure 1h). It is important to note that the potential for increased presence of subsurface chlorophyll maxima (as a result of deepening nutriclines) may be challenging to quantify seasonally via satellite data in the Chukchi Sea (Arrigo et al., 2011; Ardyna et al., 2013; Brown et al., 2015). Nonetheless, we hypothesize that because of the May declines of sea ice in the Gulf of Anadyr and resulting increases in May chlorophyll-*a*/primary production in that region, available nutrients downstream in the western Bering Strait during June are depleted, and chlorophyll-*a*/primary productivity therefore have declined over time there as well. In particular, in the western Bering Strait (within the region designated as statistically significant for June chlorophyll-*a* concentrations; Figure 1f), June chlorophyll-*a* concentrations have changed by approximately –58% (from 4.2 mg/m^3 to 1.8 mg/m^3), and June primary productivity has changed by approximately –34% (from 2,418 mg C/m^2/day to 1,606 mg C/m^2/day). These shifts represent chlorophyll-*a* trends of –1.52 mg/m^3/decade and primary productivity trends of –477.8 mg C/m^2/day/decade. However, increases in chlorophyll-*a* and primary productivity in the western Bering Strait primarily during September (not shown) counteract these June decreases, so overall annual primary productivity rates in this region are not significant. Thus, while annual productivity may not have changed substantially, observed shifts in the seasonal distribution of productivity may indeed have

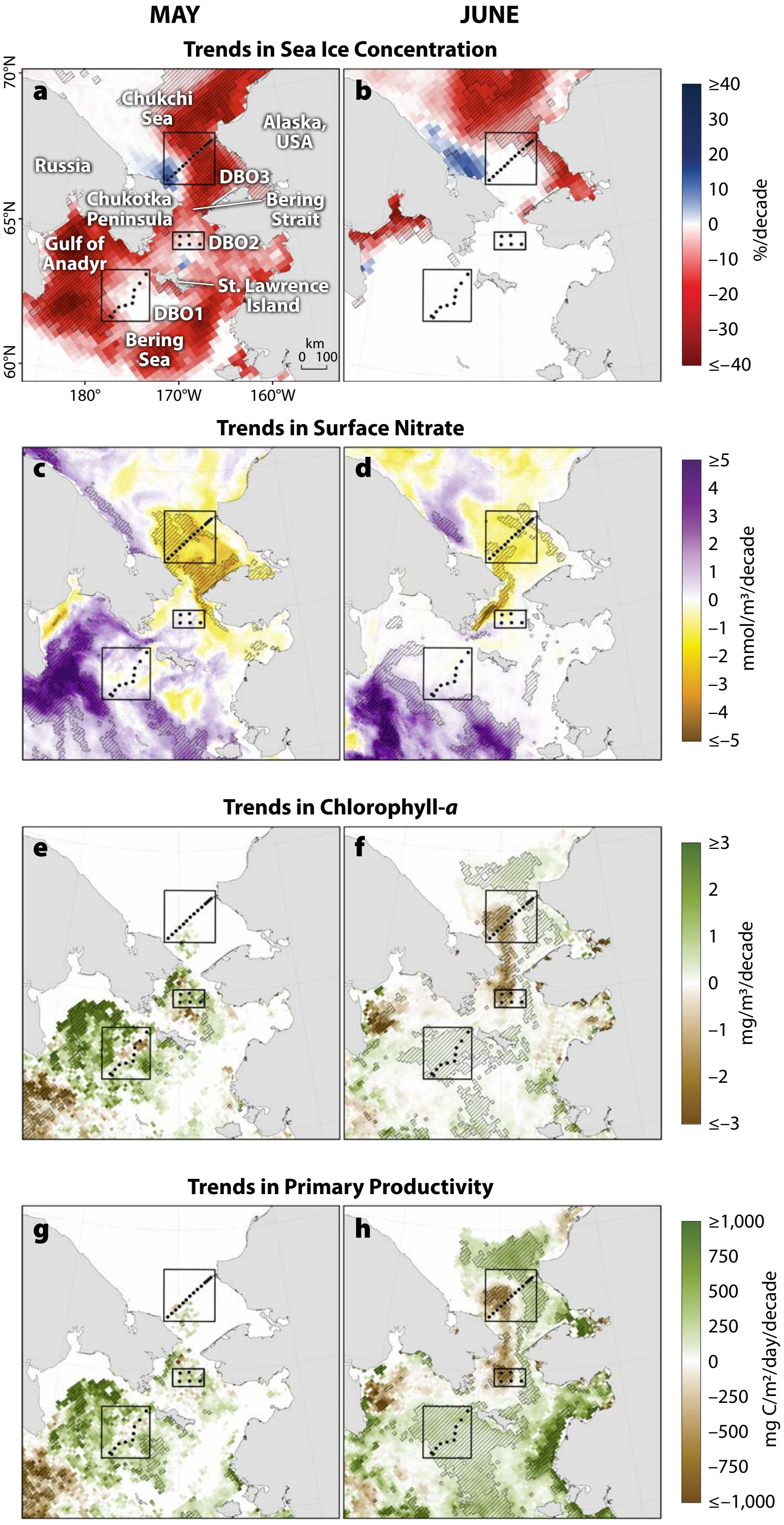

FIGURE 1. Decadal Theil-Sen median trends for May/June over the years 2003–2020 in (a,b) sea ice concentrations, (c,d) surface nitrate concentrations, (e,f) chlorophyll-*a* concentrations, and (g,h) primary productivity. Hatched regions indicate statistically significant ($p < 0.1$) trends, determined using the Mann-Kendall test for trend. Distributed Biological Observatory (DBO) sites 1, 2, and 3 (Grebmeier et al., 2019) are shown for geographic context.

profound consequences for marine ecosystem functioning across this region.

Despite measurements of overall, large-scale increases in primary productivity across the Arctic Ocean over recent decades, heterogeneity in shifts of nutrient availability to upper ocean waters across the region has also led to a spatial mosaic of both increases and decreases in productivity (Juranek, 2022, in this issue). For example, while earlier sea ice retreat can result in stronger blooms in Arctic shelf regions, increased sea ice melt can also result in reduced production in portions of the central Arctic owing to enhanced stratification (Song et al., 2021). Furthermore, moored sensor-based measurements of dissolved inorganic nitrogen (DIN) in bottom waters in the northern Bering Sea indicate high interannual variability but an overall decline of ~50% over the 2005–2017 period, with strong correlations of late summer/early fall DIN resulting in primary productivity downstream on the northern Chukchi shelf the following May (Mordy et al., 2020). Likewise, the early season declines in primary productivity in the western Bering Strait found in this study should undoubtedly have important consequences for the further downstream delivery of carbon and otherwise excess nutrients to the Herald Canyon and western/central Chukchi Shelf regions, important hotspots for biological productivity in the Arctic (Arrigo et al., 2012, 2014; Linders et al., 2017; Li et al., 2019). Changes in the seasonal and spatial distribution of spring phytoplankton blooms in the Pacific Arctic will also likely have important effects on pelagic-benthic coupling in a region with historically high benthic biomass and large populations of seabirds and marine mammals that depend upon benthic prey for survival (Grebmeier et al., 2006, 2018).

The observations of change in the western Bering Strait reported here provide an important example of the heterogeneity of ecosystem responses to climate change, where primary productivity does not always increase with declines in sea ice cover. Moreover, it is important to consider how environmental changes such as sea ice decline can have vital impacts on ecosystem functioning not only locally but also through resulting impacts on nutrient delivery downstream along a conveyor belt system of ocean currents.

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CHANGING BIOGEOCHEMISTRY OF THE ARCTIC OCEAN

SURFACE NUTRIENT AND CO_2 CYCLING IN A WARMING, MELTING NORTH

By Lauren W. Juranek

ABSTRACT. The physical system of the Arctic is changing in profound ways, with implications for the transport of nutrients to and from the Arctic Ocean as well as the internal cycling of material on shelves and in deep basins. Significant increases in Arctic Ocean primary production have been observed in the last two decades, potentially driven by enhancements to a suite of mechanisms that increase nutrient availability to upper ocean waters, including transport from adjacent subpolar regions, storm-induced mixing, and mobilization of nutrients from terrestrial pools. The relative strength of these mechanisms varies substantially within Arctic Ocean subregions, leading to a mosaic of biogeochemical responses. Changes in primary production are also driving regional changes in the biologically mediated air-sea exchange of CO_2, while warming, enhanced stratification, and increased mobilization of carbon from terrestrial pools are also driving regionally variable trends.

INTRODUCTION

As a climate-sensitive region where surface air temperature is warming at a pace more than double that of the rest of the globe (Taylor et al., 2017, Jacobs et al., 2021), the Arctic is undergoing profound change. Extensive loss of sea ice area in all months of the year (Stroeve and Notz, 2018) is affecting regional albedo and radiative heat budgets. Decreased sea ice extent and persistence is also allowing increased exchange between the upper ocean and the atmosphere, with enhanced transfer of momentum from atmospheric cyclones and storms, and greater exchange of heat in areas previously covered by ice (Crawford and Serreze, 2017; Serreze et al., 2009; Screen et al., 2011). Thinning ice and increased extent and duration of seasonal open water is increasing phytoplankton primary productivity (PP) in previously light-limited regions (e.g., Arrigo and van Dijken, 2015). Meanwhile, enhanced stratification from increased upper ocean freshwater content in deep basins restricts nutrient replenishment from deep waters, limiting PP and the exchange of gases between the atmosphere and surface waters (McLaughlin and Carmack, 2010; Haine et al., 2015; Carmack et al., 2016).

These shifting baselines in the physical system are already driving changes in the biogeochemical cycling of nutrients and carbon throughout the Arctic Ocean in both predictable and less predictable (or even counterintuitive) ways (e.g., Bates and Mathis, 2009; Tremblay et al., 2015). Bathymetry, stratification, seasonal vs. perennial ice coverage, exposure to storms, degree of river and terrestrial influence, and effects of advection from adjacent regions all determine regional-scale responses. Consequently, Arctic Ocean subregions (i.e., shelves vs. deep basins and areas positioned at Arctic gateways vs. those situated at interior locations on circulation pathways) are forced by a unique mélange of drivers, and their responses vary in both sign and magnitude. Hence, while the long-term decrease of sea ice from the Arctic Ocean is a unifying trend, the ocean's biogeochemical responses are not singular, but rather a suite of complex, regional-scale trajectories. Here, key aspects of biogeochemical change are highlighted through the lens of a foundational currency, nitrogen, which functions as the primary limiting nutrient controlling PP in the Arctic Ocean and thus is at the heart of many of the biogeochemical changes occurring throughout the region. Insights that emerge from an Arctic Ocean-wide budget of nitrogen, as well as those gleaned from understanding the regional-scale dynamics underlying integrated, Arctic Ocean net change, are discussed as are the consequences of altered nutrient dynamics for the air-sea exchange of CO_2 in the Arctic Ocean.

CHANGING NUTRIENT SUPPLY IN THE ARCTIC OCEAN

Water column nutrient distributions comprise a fundamental control on photosynthesis and, hence, the PP that forms the foundation of Arctic Ocean ecosystems. PP, and more specifically, net community production (the fraction of PP that is not respired by heterotrophs in surface waters) also facilitates the sequestration of CO_2 in the Arctic Ocean as the carbon contained in organic matter settles to a depth where, upon subsequent oxidation, the resulting CO_2 generated is separated from the atmosphere. The major limiting nutrient controlling primary production in the Arctic Ocean is nitrogen, as inorganic nitrogen (hereafter referred to as dissolved inorganic nitrogen, DIN, which includes the sum of nitrate, nitrite, and ammonium species) is typically found with phosphorus in a molar ratio much lower than the canonical Redfield stoichiometry of 16:1 (Codispoti et al., 2013; Tremblay et al., 2015). The deficiency of DIN in Arctic waters can be understood in the context of Arctic Ocean circulation and connectivity to other basins: low N:P waters from the subarctic Pacific Ocean advect into the Arctic Ocean (Yamamoto-Kawai et al., 2006; Tremblay et al., 2015), while additional DIN losses occur within the Arctic Ocean by denitrification on Arctic shelves (Figure 1; Chang and Devol, 2009). Surface waters in much of the ice-free Arctic Ocean exhibit depleted surface DIN inventories quickly after ice retreat, leading to nutrient limitation of PP and oligotrophic status during the rest of the open water season when light is abundant (Figure 2). Climate-related changes to the availability of DIN in surface waters therefore have particular significance for primary productivity and biological pump functioning.

Recent pan-Arctic remote sensing studies indicate an approximate 60% increase in Arctic PP between 1998 and 2018 in open water areas and recognize that greater availability of light and nutrients is fueling this increase (Ardyna and Arrigo, 2020; Lewis et al., 2020). Declining ice cover, increasing open water area, and decreasing sea ice persistence all clearly contribute to more light availability for photosynthesis (e.g., Pabi et al., 2008). Nutrient concentration and flux data are generally not available at sufficient spatial and temporal resolutions to quantify the importance of various mechanisms that increase nutrient supply. Consequently, hypotheses concerning PP increases fueled by changing DIN supply are

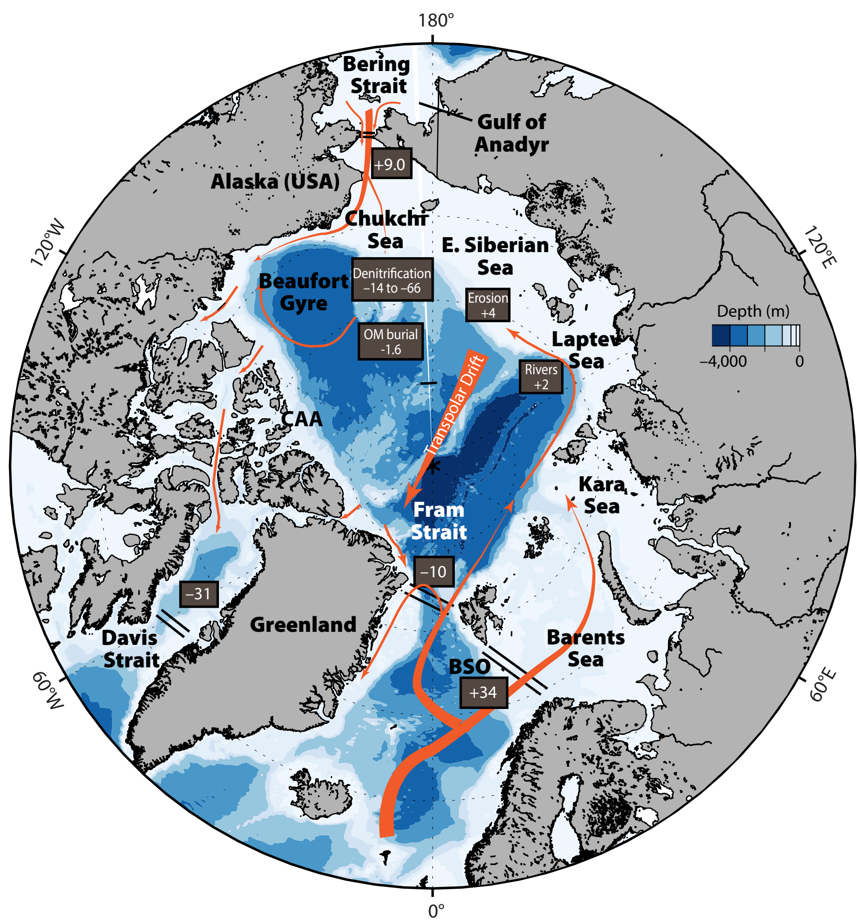

FIGURE 1. Map of the Arctic Ocean showing its gateways at Bering Strait, Fram Strait, Davis Strait, and the Barents Sea Opening (BSO). Major regional seas characterized by inflow shelves (Chukchi and Barents Seas), interior shelves (Beaufort, Kara, Laptev, and East Siberian Seas), and outflow shelves (Canadian Arctic Archipelago, CAA) are also indicated. Orange arrows provide a basic conceptual representation of major circulation pathways referred to in the text. Depth-integrated net dissolved inorganic nitrogen (DIN) transport fluxes through Arctic Ocean gateways are shown in boxes (positive values indicate net flux into the Arctic Ocean, negative values indicate flux out) as reported in Torres-Valdés et al. (2013). Estimates of internal DIN sources and sinks as discussed in the text are also indicated, with positive/negative values indicating DIN sources/sinks, respectively. All quantities are indicated in kmol N s^{-1}.

largely based on inference. As an example, remote sensing indicates that some of the largest increases in PP and chlorophyll concentration occur in the Barents and Chukchi Seas (Lewis et al., 2020), regions known as Arctic "inflow" shelves (Carmack et al., 2006). These regions are situated at Arctic gateways where prevailing circulation advects water masses (and the nutrients they contain) from adjacent subarctic regions (**Figure 1**). Recent increases in water transport through Arctic gateways (Årthun et al., 2012; Woodgate, 2018; Polyakov et al., 2020) have been hypothesized to increase DIN supply and fuel observed PP and chlorophyll increases (Lewis et al., 2020).

In addition to these remote nutrient inputs from adjacent subarctic seas, a suite of local delivery mechanisms spurred by a changing physical environment are also likely to impact nutrient availability in sunlit waters (Tremblay et al., 2015). These mechanisms are governed by regionally specific physical characteristics (bathymetry, relative ice cover, stratification, wind patterns, and degree of terrestrial influence), as well as factors related to differences in the biological community (grazing rates, community composition); thus, they are spatially variable and operate on a spectrum of inherent timescales. Together, these factors influence both the degree to which nutrients are seasonally replenished in winter and the degree to which episodic nutrient fluxes occur during the ice-free season (Carmack and Chapman, 2003; Pickart et al., 2013; Randelhoff and Sundfjord, 2018; Randelhoff et al., 2020). Mobilization of terrestrial and shelf-derived material from increased river discharge, thawing permafrost, and enhanced coastal erosion also plays an important role in certain regions (Frey and McClelland, 2009; Le Fouest et al., 2013; Terhaar et al., 2021).

A Baseline DIN Budget for the Arctic Ocean

To provide important context for how DIN supply and availability may be changing in various subregions of the Arctic Ocean, it is helpful to first start with a zoomed out, pan-Arctic scale view of how known DIN sources and sinks contribute to this ocean's baseline budget. The budget approach, a tried-and-true tool in the biogeochemistry playbook, identifies important knowledge gaps and helps provide important context regarding potential sensitivities to perturbations. Multiple attempts to construct DIN budgets for the Arctic Ocean have been undertaken in the last 50 years, often with spatially and temporally sparse data (see Torres-Valdés et al., 2013, and references therein). The most recent and comprehensive effort to date used a model of depth-resolved circulation and measured nutrient profiles from Arctic gateway regions in summer to constrain the DIN inputs and outputs via transport (Torres-Valdés et al., 2013). This analysis found that the major net sources of DIN to Arctic waters were via inflow gateways

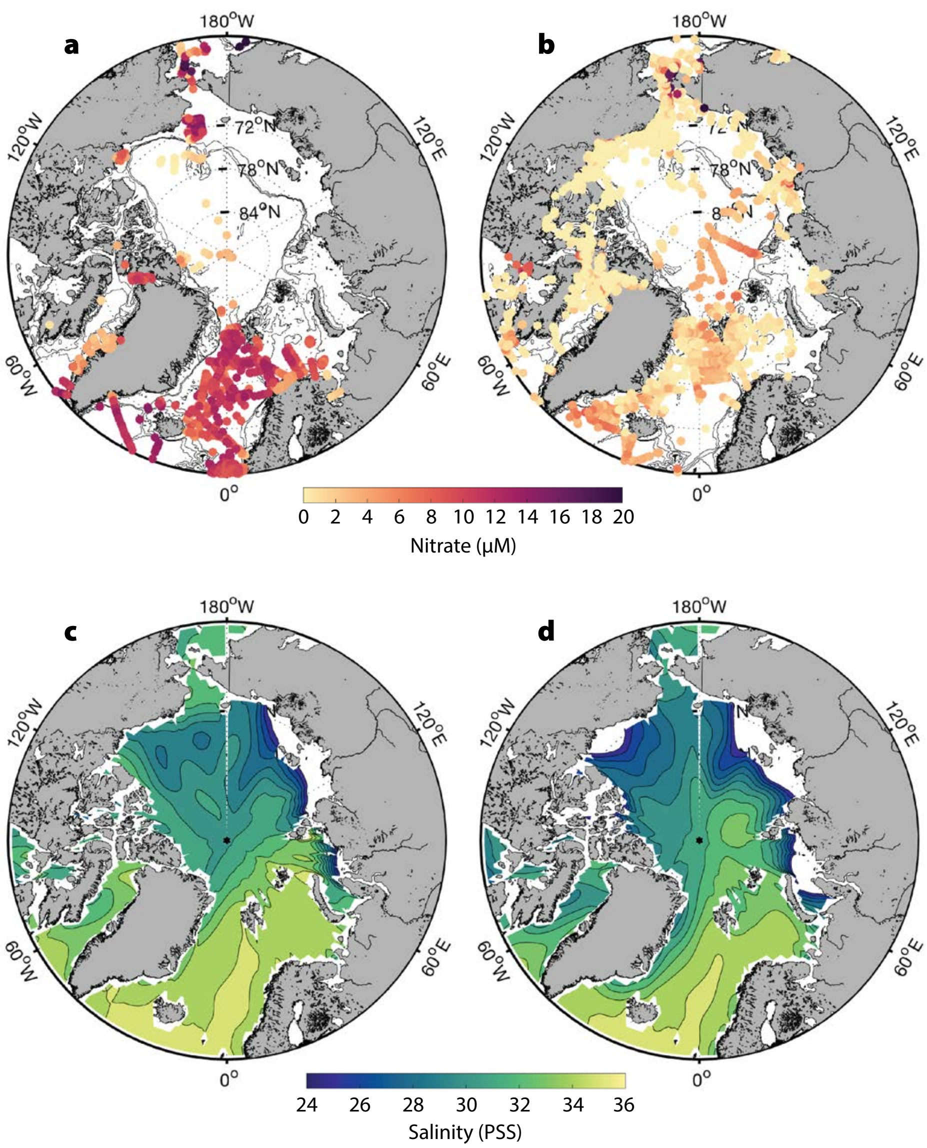

FIGURE 2. Seasonal patterns of nutrients and salinity in the Arctic Ocean. Nutrient data were compiled from Codispoti et al. (2013) as well as additional sources reported in Randelhoff et al. (2020). Salinity is from a seasonal climatology based on the World Ocean Database (Boyer et al., 2014). (a) Winter (November–March) surface (<10 m) nitrate concentration. (b) Post-bloom (August–September) surface nitrate concentration. (c) Winter (January–March) salinity climatology. (d) Summer (July–September) salinity climatology. The nutrient scale has been attenuated to make regional differences more discernible.

at the Bering Strait (9.0 kmol s^{-1}) and the Barents Sea Opening (34 kmol s^{-1}; Figure 1). The Fram Strait and Davis Strait gateways also had substantial DIN inputs, but they were offset by large nutrient outputs in equatorward currents. Fram Strait was a net exporter of DIN (−10 kmol s^{-1}), with a balance of inputs (53 kmol s^{-1}), primarily via the West Spitsbergen Current, and outputs (−63 kmol s^{-1}) from the East Greenland Current. The net DIN transport in Davis Strait (−31 kmol s^{-1}) was dominated by the outflow on the western side (−38 kmol s^{-1}), with a weak inflow on the shallow waters of the eastern side (6 kmol s^{-1}). Perhaps more importantly, the sum of all DIN inputs and outputs at the gateways was 1 kmol s^{-1}, indistinguishable from zero, given the methodological uncertainties.

A near-zero net DIN transport is an intriguing result. It suggests that the nutrient budget is balanced with respect to transport, which indicates that there cannot be additional, internal DIN losses within the Arctic Ocean without additional sources. Otherwise, DIN inventories would deplete over time. However, there are a few important caveats. The Torres-Valdés et al. (2013) analysis relied solely on summer transport and nutrient profiles (primarily from a single season in 2005, with some sensitivity studies); thus, seasonal and interannual variability in nutrient fluxes was not captured. As discussed in the following section, the advection of nutrients through Arctic gateways in winter months along with interannual variability in DIN transports are likely critical for setting the inventory of nutrients within the Arctic Ocean. To fully close the nutrient budget requires resolving coupled transport and nutrient fluxes over timescales relevant to the ocean's circulation, observations that are not yet available.

Nonetheless, it is still useful to evaluate the implications of a net zero transport of DIN through the gateways. Internal system losses of DIN are well documented, and they could not be sustained indefinitely in the absence of additional sources if net transport of DIN were negligible. Loss of DIN by microbially mediated denitrification (conversion of fixed and bioavailable DIN to N_2 and N_2O) is estimated to be a substantial internal sink term of 14 to 66 kmol N s^{-1} (−6 to −29 Tg N yr^{-1}; Chang and Devol, 2009; Figure 1). Denitrification is particularly prevalent on shallow Arctic shelves that receive a high flux of organic matter (Chang and Devol, 2009; Granger et al., 2018). Additional loss of DIN is expected through sedimentary burial of organic matter. The majority of organic matter produced via PP is respired back to DIN in surface or subsurface waters, but a small fraction escapes oxidation and is buried (primarily on shallow Arctic shelves and adjacent continental slopes, where the settling time is reduced); estimated burial is 0.7 Tg N yr^{-1} (3.7 Tg C yr^{-1}; Stein and Macdonald, 2004), which equates to 1.5 kmol N s^{-1}. These internal sinks are partially offset by additional DIN and dissolved organic nitrogen (DON) from terrestrial sources, that is, mobilized by rivers and coastal erosion within the Arctic. These sources affect regional biogeochemical cycling but are believed to be small at the scale of the Arctic Ocean: ~1.5–1.7 kmol N s^{-1} (Le Fouest et al., 2013; Torres-Valdés et al., 2013). DON flux through Arctic gateways may also represent an important source, but at present it is poorly constrained (Torres-Valdés et al., 2013; Tremblay et al., 2015).

The knowledge gaps that emerge from the large-scale Arctic Ocean nutrient budget point toward areas where there are clear research needs. Resolving nutrient inputs at Arctic gateways over a full annual cycle, along with quantifying interannual variability or trends, is of utmost importance for understanding how PP and biologically mediated CO_2 uptake may change in the Arctic Ocean. Better constraint of DON transport/utilization and reduction in the uncertainty of the denitrification sink might also help to bring the budget toward closure. However, the budget analysis also provides important context for understanding what is known about changing sources and sinks, as well as coupled physical and biogeochemical processes that do not act as sources or sinks on an Arctic-wide scale but do impact regional DIN availability in the upper layers where PP and CO_2 uptake occurs. The next few sections tackle what is known regarding changing nutrient supply via Arctic Ocean gateways, changing nutrient supply via rivers, and changing upper ocean nutrient availability from physical processes operating over a range of spatial and temporal scales.

Changing Nutrient Supply at Arctic Inflow Shelves

Arctic Ocean gateway nutrient fluxes calculated by Torres-Valdés et al. (2013) relied on data from summer 2005, but observations from Arctic inflow shelves suggest that transport is changing significantly in these regions. At the Bering Strait gateway, a ~50% increase in the volume transport has been observed from the 1990s through 2014 (i.e., 0.7 Sv to 1.1 Sv; Woodgate, 2018), leading some to hypothesize that this corresponds to increased DIN input to the areas immediately downstream (e.g., Ardyna and Arrigo, 2020; Lewis et al., 2020). However, the DIN flux (mass/time) is a product of both the volume transport (volume/time) and DIN content of various water masses (mass/volume) entering Bering Strait. Higher-nutrient water is derived from outer slope waters of the Bering Sea, and in particular waters that circulate in the Gulf of Anadyr to the southwest of Bering Strait (see sidebar by Frey et al., 2022, in this issue). Terrestrial-origin fresh waters conveyed north by the Alaska Coastal Current on the eastern side of Bering Strait tend to be low in nutrients (Codispoti et al., 2013). Long-term trends in salinity monitored at Bering Strait indicate that the transport has freshened significantly, particularly in winter (Woodgate and Peralta-Ferriz, 2021), which suggests that a direct correlation between transport and DIN flux cannot be presumed.

Several lines of evidence suggest that delivery of DIN through Bering Strait may in fact have been decreasing in the past decade. Moored sensor-based observations of near-bottom nitrate concentrations in the northern Bering Sea in late summer/early fall indicate an overall 50% decline over the 2005–2017 period (from ~20 μM to ~10 μM), with a rebound in 2018–2019 (Mordy et al., 2020). These late summer/early fall nitrate concentrations were also found to be highly correlated with those on the northern Chukchi shelf in mid-May, which roughly corresponds to the timing of sea ice retreat and associated spring phytoplankton bloom in this region. In a separate analysis reported in this special issue, Frey et al. (2022) found a decline in remotely sensed PP in western Bering Strait waters typically influenced by high-nutrient Anadyr water. Anomalously high PP in May in the Gulf of Anadyr, hypothesized to be driven by earlier ice retreat, mirrored a decrease in PP in downstream waters of the western Bering Strait in June (34% over 2004–2010), suggesting that nutrients were being consumed in the northern Bering and depleting nutrients that would normally allow PP to occur downstream in the Chukchi Sea (Frey et al., 2022, in this issue).

On the other side of the Arctic Ocean in the Atlantic gateway region, the temporal trend in DIN flux is similarly unclear. Observations suggest a doubling of warm, Atlantic-origin water in the Barents Sea—a phenomenon termed the "Atlantification" of the European Arctic sector (Årthun et al., 2012). The heat content of this water mass has been implicated in the northward migration of the seasonal ice zone (Oziel et al., 2017); in addition, as a major source of nutrients to the region, this water mass might be presumed to support higher rates of PP on the Barents Sea inflow shelf (Henley et al., 2020). However, the degree to which the nutrient content of Atlantic water can be utilized by phytoplankton is influenced by stratification and ice cover, which interact with local wind forcing to set seasonal nutrient replenishment in winter as well as intermittent pulses of nutrients into the system during the open water season (Figure 2; Slagstad et al., 2015; Wiedmann et al., 2017; Henley et al., 2020). The depth of mixing controls the inventory of DIN available for PP in the stratified surface layer; thus, even though Atlantic water may convey a reservoir of nutrients into the Arctic Ocean, it has little influence on Arctic biogeochemical cycling unless it reaches surface waters. An ocean biogeochemical model run under a future warming scenario suggests a decrease in productivity in the southern Barents Sea inflow region over the next century due to enhanced thermal stratification, which reduces nutrient replenishment in winter (Slagstad et al., 2015). In addition, a decline in the nitrate concentration of inflowing Atlantic water in the Barents Sea has been observed over the 1990–2010 period; variations in the source region of waters feeding into the Barents Sea (due to climate-ocean responses to the North Atlantic Oscillation) may play a role in this trend (Rey, 2012; Oziel et al., 2017).

In addition to nutrient-based controls on PP on inflow shelves, the importance of other processes that regulate biomass, including advection of phytoplankton and grazers from adjacent regions (Vernet et al., 2019; Wassmann et al., 2019), should be considered. Recent biogeochemical modeling in the Barents Sea and Fram Strait regions suggests that advection of phytoplankton from south to north along major currents supports a substantial proportion of biomass and resulting PP (Vernet et al., 2019). The importance of advected vs. in situ production is seasonally and spatially variable, but the upshot is that this advection allows more northerly regions to maintain much higher rates of PP than they would with no advective inputs. This advected biomass ultimately amounts to a 0.76 Tg C yr^{-1} supplement of organic carbon (and its stoichiometric equivalent of organic N) to the Arctic Ocean north of Svalbard, with more southerly subregions within the Atlantic water inflow receiving higher subsidies (Vernet et al., 2019). Advection of grazers (e.g., copepods and microzooplankton) northward also regulates existing biomass and is an important control on PP in inflow shelf regions (Lavrentyev et al., 2019; Wassmann et al., 2019). Thus, physical and ecological factors that influence grazer communities (surface warming, changes in advective transport, changing spatial patterns of phytoplankton biomass) will ultimately influence Arctic Ocean PP trends as well.

Increasing Influence of Terrestrial Nutrient Sources

Recent studies also implicate nutrients supplied by coastal erosion and rivers as having an increasingly important role in supporting observed PP increases and influencing coastal biogeochemical cycling in the Arctic Ocean. Increased river discharge, thawing permafrost with deepening active layers, and enhanced shoreline erosion due to a loss of buttressing ice in fall and winter all intensify the land-ocean exchange of material (Frey and McClelland, 2009; McClelland et al., 2012). One recent modeling analysis that sought to quantify the impact of terrestrial sources on the Arctic Ocean indicates that DIN supplied by coastal erosion and rivers (estimated as 1.6 Tg N yr^{-1} and 1.0 Tg N yr^{-1}, respectively) supports one-third of Arctic PP on an annual basis (9%–11% for rivers and 19%–41% for coastal erosion; Terhaar et al., 2021). Consistent with prior work (e.g., Peterson et al., 2002; Frey and McClelland, 2009; Holmes et al., 2012), the majority of the terrestrially derived DIN sources were focused in the Eurasian Arctic (East Siberian, Kara, and Laptev shelves), where the Yenisey, Lena, and Ob', the three largest Arctic rivers by annual discharge and the fifth, sixth, and thirteenth largest rivers globally, respectively, are located. However, the N supply was only estimated to support a biomass increase (new production) of 17 Tg C yr^{-1}, while the simulated increase in productivity was eight times the biomass increase (140 Tg C yr^{-1}). Hence, the large modeled

PP response was mostly from continued recycling of the initial (modest) DIN input (i.e., regenerated production; Dugdale and Goering, 1967). This finding is consistent with prior analyses that also found modest contributions of river-derived nutrients to new production (Tank et al., 2012; Le Fouest et al., 2013) due to the carbon-rich and nitrogen-poor nature of Arctic rivers (Holmes et al., 2012). The distinction between new vs. regenerated PP is important because these two types of PP influence carbon and nutrient cycling differently. Regenerated production is a zero-sum process. It does not involve a net biological uptake of CO_2 because regeneration and reuse of N contained in organic matter also regenerates CO_2. New production is not zero sum, and can support biomass transfer to higher trophic levels, thus fueling Arctic ecosystems. Alternatively, organic matter produced during new production can sink to subsurface water masses that are out of reach of seasonal mixing horizons; therefore, the carbon and nitrogen contained in settling organic matter becomes isolated from further biogeochemical cycling in the surface environment.

Observations from the recent Arctic GEOTRACES mission provide additional evidence of an increasing signature of terrestrial and shelf inputs into Arctic Ocean waters. Kipp et al. (2018) found that an increase in radiotracer activities (^{228}Ra and ^{226}Ra) in the Transpolar Drift of the central Arctic Ocean (**Figure 1**) in 2015 relative to 2007 is indicative of increased shelf-based inputs from East Siberian and Laptev Sea shelves). They hypothesized that disturbance of a large ^{228}Ra reservoir in shelf sediments by enhanced wind-driven mixing over a longer open water season was the primary driver of these changes. These findings are broadly consistent with those of a coastal erosion modeling study (Terhaar et al., 2021) that found the largest modeled increases in marine PP from terrestrial and sedimentary nutrient sources occur on the East Siberian, Laptev, and Kara shelves.

The Kipp et al. (2018) study as well as aforementioned river and coastal erosion studies all paint a picture of Eurasian shelves that are "interior" in Arctic Ocean circulation pathways (**Figure 1**; Carmack et al., 2006) and heavily influenced by large Arctic rivers as sites of intensified land-ocean biogeochemical cycling and sediment mobilization. This unique regional character is important to note because, as described above, these regions exhibit a different suite of responses to Arctic Ocean change than are seen in other regions.

Changes to Seasonal Nutrient Replenishment

In addition to nutrient sources from rivers and transport through gateways, processes that affect the depth distribution of nutrients over an annual cycle are also critical influences on biogeochemical nutrient and carbon cycling in the Arctic Ocean. In seasonally and perennially ice-free waters, pre-bloom nutrient inventories at the surface are well correlated with patterns of annual PP throughout the Arctic Ocean (**Figure 2**; Tremblay and Gagnon, 2009; Tremblay et al., 2015; Randelhoff et al., 2020). The association is somewhat intuitive because DIN inventory amassed during winter mixing determines the reservoir available to phytoplankton when sea ice seasonally thins and retreats and light levels become sufficient for growth (Codispoti et al., 2013; Tremblay et al., 2015; Randelhoff and Sundfjord, 2018). However, the degree of winter replenishment varies across Arctic shelves and deep basins, governed by regional stratification and the depths of winter mixing, and the nitracline (Wassmann and Reigstad, 2011; Tremblay et al., 2015; Randelhoff et al., 2020). Typically, shallow shelves nearest to nutrient sources at the gateways exhibit more robust replenishment while open waters overlying deeper bathymetry and strong stratification show weakest replenishment (see winter nitrate concentrations in **Figure 2**). For example, the Chukchi Sea in the Pacific Arctic sector is characterized by a broad, shallow shelf (ca. 50 m) and a relatively shallow nitracline (ca. 20–40 m); in winter, storms and convective mixing completely erode the seasonal stratification, and the nutrients accumulated in the near-bottom layer from remineralization of organic matter over the summer are redistributed throughout the water column (**Figure 3**; Pacini et al., 2019; Mordy et al., 2020). The Barents Sea shelf is deeper (ca. 200 m), but this region has also historically been characterized by extensive replenishment of DIN by convective and storm-driven mixing in fall/winter (**Figure 2**; Slagstad et al., 2015; Randelhoff et al., 2020). The strong replenishment contributes to the very high rates of PP in these locales during ice retreat in spring (Hill and Cota, 2005; Codispoti et al., 2013; Matrai et al., 2013).

In contrast, the depth of the nitracline in the deep Canada Basin of the central Arctic Ocean exceeds that of typical winter mixing depths (McLaughlin and Carmack, 2010; Carmack et al., 2016; Randelhoff et al., 2020). In regions of the high-latitude central Arctic Ocean that have transitioned from perennial to seasonal ice cover, nutrient replenishment is also weak, but a lack of complete DIN drawdown during the vegetative season in these regions indicates that light limitation still plays an important role in limiting PP (**Figure 2**; Randelhoff et al., 2020); hence, at present, the role of seasonal nutrient replenishment is not as important here, but this pattern is expected to change with continued declines in ice cover (Slagstad et al., 2015).

The degree of seasonal nutrient replenishment is certainly sensitive to future climate forcing. For example, biogeochemical modeling indicates that PP in the southern Barents Sea will be restricted by future warming and enhanced thermal stratification (Slagstad et al., 2015). Observations suggest that enhanced stratification in the Beaufort gyre has already depressed the nitracline, limiting the resupply of DIN to surface waters (McLaughlin and Carmack, 2010), consistent with both the low PP rates typically observed in this region and an observed shift to smaller picoplankton that are better adapted for nutrient-limited conditions (Li et al., 2009). Meanwhile, warming surface temperatures may fuel enhanced microbial loop activity and facilitate less export of organic material and more regeneration of nutrients in the surface layer (Kirchman et al., 2009). Biogeochemical modeling also predicts further decreases in PP in the Beaufort gyre in the future (Slagstad et al., 2015). The fundamentally different conditions on inflow shelves and in deep basins with respect to declining ice cover and seasonal nutrient replenishment typify the mosaic of Arctic Ocean subregion responses to warming-induced physical system change. On inflow shelves, decrease in ice coverage over winter months facilitates mixing and momentum transfer, whereas in deep basins enhanced haline stratification limits seasonal replenishment. Again, these differences demonstrate that understanding the unique character of Arctic Ocean subregions is critical to understanding biogeochemical responses to climate-driven changes.

Episodic Nutrient Delivery by Storms and Wind Events

While changes in transport and winter replenishment set total nutrient inventories available to phytoplankton in the upper water column for early season growth, episodic pulses of nutrients contributed by regional wind-forcing and/or current-bathymetry interactions can be important for maintaining productivity throughout the post-bloom, summer, open-water season when nutrients are scarce (Pickart et al., 2013; Ardyna et al., 2014; Nishino et al., 2015; Wiedmann et al., 2017). Because these mechanisms help to relieve nutrient limitation and support continued lower trophic level production over a lengthening growing season, they may be increasingly important in a warming Arctic.

Enhancement of shelf break upwelling by the expansion of the seasonal melt zone has long been recognized as an important mode by which PP might be enhanced in a warming Arctic (Carmack and Chapman, 2003), though at more spatially and temporally reduced scales. Reduced or minimal ice cover at continental shelf breaks facilitates the transfer of wind momentum; when prevailing high and low atmospheric pressure centers result in directional, upwelling-favorable winds and shelf break depths are shallow enough to constrict flow and allow horizontal divergence (Randelhoff and Sundfjord, 2018), nutrient-rich waters are brought to the surface. This is particularly true along the Beaufort Sea shelf break and in the vicinity of Barrow Canyon in the Northeast Chukchi Sea (Pickart et al., 2013). While much of the Eurasian Arctic sector is characterized by relatively deep shelves, conditions for upwelling may be favorable at the comparatively shallow Laptev Sea shelf break (Randelhoff and Sundfjord, 2018).

Analysis of long-term wind and mooring data in the vicinity of the Beaufort shelf break indicates that upwelling can be induced by moderate easterly winds (threshold of 6 m s^{-1}) and that the frequency of upwelling-favorable events has likely increased in recent decades (Pickart et al., 2013). The estimated upward DIN flux associated with these events could support significant rates of new production (average of ~400 mmol C m^{-2} per storm) if all supplied DIN is converted to biomass, but the extent to which this occurs is presently unknown. Remotely sensed and ship-based observations do indicate clear PP response to coastal upwelling events (Pickart et al., 2013), and the long-term satellite chlorophyll record notably indicates increased concentrations at both the Beaufort and Laptev Sea shelf breaks (Lewis et al., 2020).

The duration of upwelling events likely plays a role in their overall impact—longer events will allow more time for phytoplankton communities to respond and draw down available DIN inventories. Retentive circulation features facilitated by current-bathymetry interactions (e.g., Okkonen et al., 2011) may extend PP responses beyond the lifetime

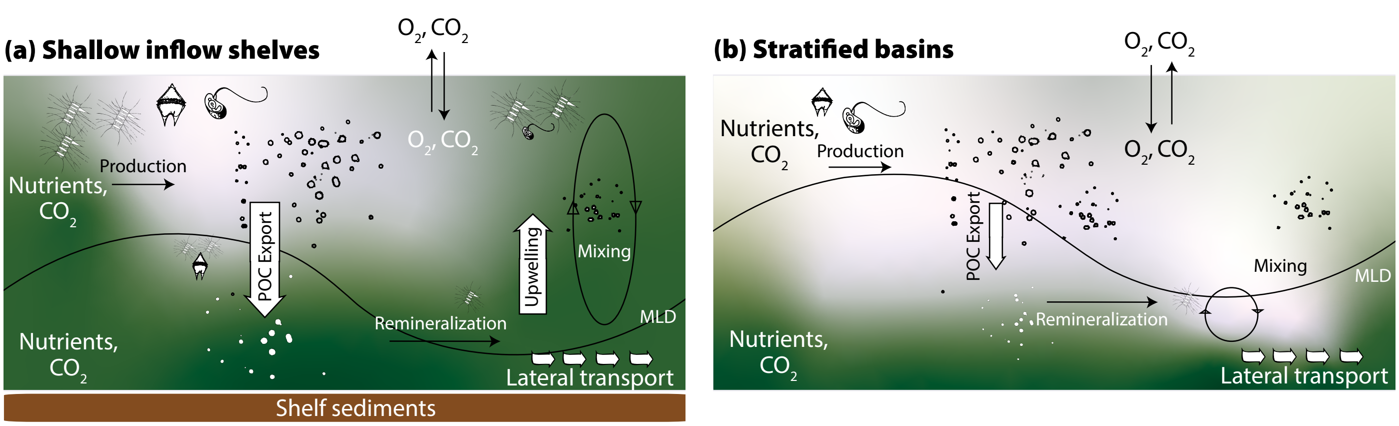

FIGURE 3. Conceptual diagram of nutrient replenishment mechanisms on (a) shallow inflow shelves, and (b) stratified deep basins. Green shading indicates relative nutrient availability. On inflow shelves, advective nutrient inputs from lower latitudes and strong replenishment due to storm-induced and winter mixing supports high rates of primary production (PP) and organic matter export. Stratified interior shelves and basins have weaker winter nutrient replenishment and storm-induced mixing, with consequent lower PP rates. MLD = mixed layer depth.

of the initial wind forcing. Recent work also suggests that shear and instabilities related to frequent changes in wind forcing can induce higher rates of cross-isopycnal nutrient flux in the Chukchi Sea (Beaird et al., 2020). In contrast to the "reversible" nutrient fluxes facilitated by temporary upwelling events, these "non-reversible" turbulent nutrient fluxes enhance transfer of N from nutrient-rich bottom waters to shallower mid-water column depths where light is sufficient to fuel photosynthesis.

More generally, there is growing recognition that turbulent and storm-induced nutrient fluxes away from shelf breaks may also play an increasingly important role in supporting higher PP in the Arctic Ocean as the seasonal ice zone and open water growing seasons expand. An analysis of satellite chlorophyll from 1998 to 2012 found increased prevalence of fall blooms throughout the Arctic Ocean attributed to greater frequency of high-wind events during open water conditions in September and October (Ardyna et al., 2014). The most significant increases in fall bloom occurrence were on inflow shelves (Chukchi, Barents), Eurasian interior shelves (Siberian, Laptev, Kara), and ice-free portions of the central Arctic. More recently, a biogeochemical modeling study found that high-frequency winds can facilitate higher Arctic Ocean primary productivity by two main nutrient-delivery mechanisms: first, and most significant, was enhanced and earlier deepening of mixed layer and nutrient entrainment in fall when light was still sufficient to allow phytoplankton blooms to occur; second, a prolonged mixing period in winter enhanced nutrient inventories that could fuel spring productivity (Castro de la Guardia et al., 2019). Thus, an increase in mixing associated with high wind events as the open water season expands is likely to manifest in both spring and fall. Evidence of earlier spring blooms has also been noted in some areas, including the Canadian Arctic Archipelago, Baffin Bay, and the Kara Sea (Kahru et al., 2011).

IMPLICATIONS FOR REGIONAL CHANGES IN AIR-SEA CO_2 EXCHANGE

The coupling of carbon, nitrogen, and phosphorus in biologically mediated processes (Redfield et al., 1963) means that changing patterns of nutrient supply and consequent changes to marine PP are inextricably linked to carbon cycling as well. However, changes to the physical system (warming, increased river discharge and increasing freshwater content in the Arctic Ocean basins, sea ice loss, changing wind speeds) also exert strong control on carbon exchange at the atmosphere-ocean and the terrestrial-ocean boundaries. While a full review of the Arctic Ocean carbon cycle and important changes is not in the purview of this review (readers are directed to some excellent reviews on the topic, e.g., Bates and Mathis, 2009, and Olsen et al., 2015), here, the focus is on the ways that inorganic carbon cycling, and in particular exchanges of CO_2 between atmosphere and ocean, are responding to the physical and biological system changes mentioned in previous sections.

Changes to Arctic Ocean CO_2 Uptake Due to Changing Primary Productivity

Regions of the Arctic Ocean that have seen marked increases in PP over the last several decades, in particular the Arctic gateway inflow shelves, will also act as strong biologically mediated sinks for CO_2 on a seasonal basis as organic matter is produced in the surface and exported to depth. As exported organic matter is respired at depth, seasonal stratification prevents mixing of accumulated respiratory CO_2 to the surface where it would otherwise outgas, much as it restricts the resupply of DIN that also accumulates (Figure 3). Input of CO_2 associated with respiration of exported organic matter at depth also contributes to seasonal undersaturation of calcium carbonate minerals (i.e., corrosivity; Bates and Mathis, 2009). Historically, this biologically mediated organic carbon pump has helped the Chukchi and Barents Seas to maintain strongly undersaturated CO_2 at the surface and has facilitated these areas functioning as regions of enhanced ocean uptake of CO_2 from the atmosphere, while interior shelves and deep basins with low PP rates represent much weaker sinks (Bates and Mathis, 2009; Yasunaka et al., 2016; Pipko et al., 2017). The recently reported increases in PP on some Arctic shelves therefore have the potential to enhance oceanic uptake of CO_2 so long as they are associated with export of material to depth and not with regenerated production, where CO_2 is alternately consumed and released by photosynthesis and respiration, respectively (Dugdale and Goering, 1967; Tremblay et al., 2015). For example, the substantial proportion of PP fueled by riverine and coastal erosion sources of DIN found by Terhaar et al. (2021) would only modestly contribute to enhanced biological CO_2 uptake because the majority of the PP in that study was determined to be regenerated. In contrast, a combination of modeling and observations suggests an increase in continental shelf PP and biological CO_2 uptake over a longer growing season on inflow shelves (Tu et al., 2021) and indicates the importance of high rates of PP on the Chukchi shelf for offsetting reduction in CO_2 uptake associated with surface temperature increases (Ouyang et al., 2020). In Arctic Ocean deep basin surface waters, a reduction of an already weak biologically mediated CO_2 sink due to enhanced stratification and associated deepening of the nutricline (McLaughlin and Carmack, 2010) has already been noted (Cai et al., 2010; Else et al., 2013; Ouyang et al., 2020).

PP associated with the previously described shelf break upwelling and fall phytoplankton blooms warrants additional discussion with respect to new/regenerated production and biologically mediated air-sea CO_2 exchange. The supply of DIN from deep waters that fuels these blooms also brings excess CO_2, leading to significant outgassing, as has been noted in several studies

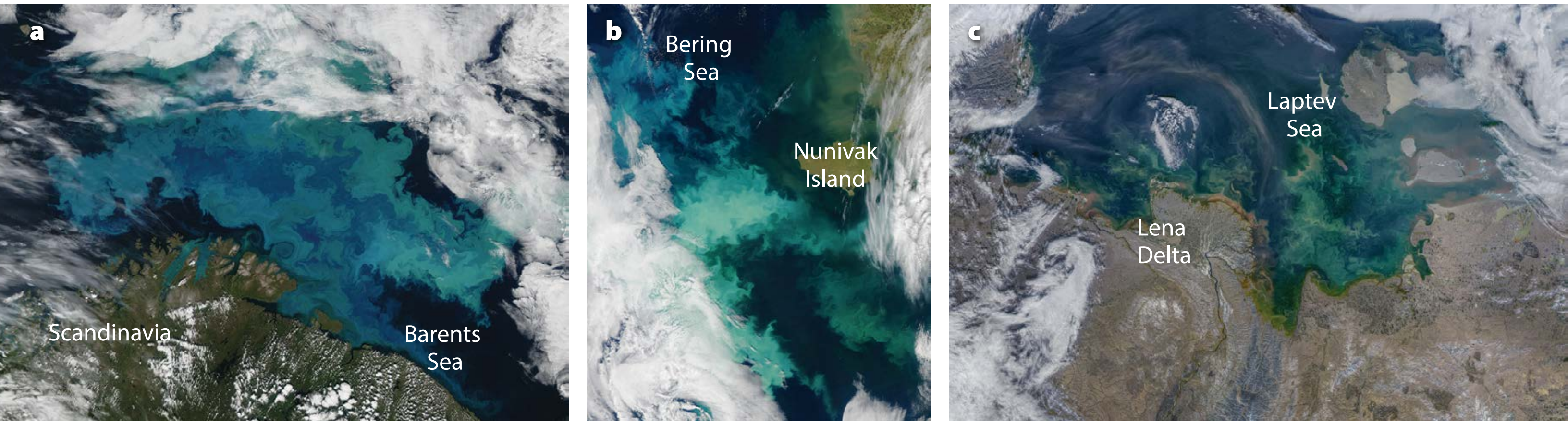

FIGURE 4. Remotely sensed visible images from MODIS Aqua show coccolithophore blooms in the (a) Barents Sea and (b) Bering Sea. (c) Laptev Sea turbidity seen here is associated with terrestrial material delivered by the Lena delta. *(a) and (b) NASA images courtesy of Jeff Schmaltz, MODIS Rapid Response Team, NASA GSFC; (c) NASA image by Norman Kuring/NASA's Ocean Color Web, using MODIS data from NASA EOSDIS/LANCE and GIBS/Worldview*

(Mathis et al., 2012; Hauri et al., 2013; Evans et al., 2015). Consumption of DIN at the surface during the phytoplankton bloom helps to mitigate this outgassing by drawing down surface water CO_2; hence, the timescale of DIN removal during a bloom helps to set the net source/sink status of CO_2 flux during these upwelling events. Whether or not these events represent new vs. regenerated production depends on the depth from which nutrient-rich waters are sourced: DIN supplied from shallow horizons where organic matter produced earlier in the season has been respired would not, in an annual budget sense, be considered new production, while DIN supplied from previously untapped reservoirs would.

Additional potential shifts in phytoplankton community composition in response to warming and other physical system changes may also reduce the efficiency of biologically mediated CO_2 uptake in the Arctic Ocean. Already, the Atlantification of the southern Barents Sea and the northward migration of the polar front have been implicated in the proliferation and northward expansion of coccolithophore blooms in this region (Neukermans et al., 2018, and references therein; Figure 4). Formation of $CaCO_3$ shells reduces alkalinity of surface waters and increases the partial pressure of CO_2 in surface waters ($pCO_{2\,w}$, where subscript w denotes water), weakening the capacity for air-sea CO_2 uptake. Coccolithophores tend to proliferate under conditions expected in this region in the future (i.e., warm waters containing low to moderate nutrients, and shallow mixed layers; Balch, 2018). While coccolithophore blooms are not common in the Chukchi Sea, they have been noted in the adjacent Bering Sea (Napp and Hunt, 2001; Ladd et al., 2018; Figure 4). The overall consequences of these ecological shifts for net regional CO_2 uptake will require continued monitoring and ecosystem modeling to resolve.

Changes in Abiotic Drivers of Arctic Ocean CO_2 Uptake

Warming and freshening of Arctic Ocean surface waters will also impact the source/sink status of some regions, particularly deep basins and some interior shelves where biologically mediated rates of CO_2 uptake are low. The expansion of the seasonal ice zone and reduction in sea ice extent in theory presents an opportunity for enhanced ocean uptake of CO_2, as cold high-latitude surface waters can now more readily communicate with the atmosphere (Olsen et al., 2015), but warming and freshening of Arctic basins counter this potential. Increasing $pCO_{2\,w}$ in the Beaufort Sea over the last few decades, an expected outcome of warming, has already been noted in a number of studies (Cai et al., 2010; Else et al., 2013; Ouyang et al., 2020), resulting in reduced regional CO_2 uptake. Seasonal freshwater input from sea ice melt or river discharge (Carmack et al., 2016) additionally reduces the capacity of these waters to buffer against additions/removals of CO_2 (by biological or abiotic processes), leading to reduced uptake capacity with additions of CO_2 (Rysgaard et al., 2011; Takahashi et al., 2014; Ouyang et al., 2020). Increasing thermal stratification in the Barents Sea is also expected to reduce the CO_2 sink in this region in the future. Indeed, observations already indicate increasing $pCO_{2\,w}$ and decreasing CO_2 uptake in the southern Barents Sea (Yasunaka et al., 2016). This contrasts with the other inflow shelf, the Chukchi, where biotic factors appear to be dominating over warming-related reductions (Ouyang et al., 2020; Tu et al., 2021).

INTENSIFIED LAND-OCEAN CARBON EXCHANGE ON EURASIAN/SIBERIAN SHELVES

Generally, discharges of Arctic Ocean rivers are organic carbon rich and DIN poor (Holmes et al., 2012; McClelland et al., 2012). Thus, while the effect of PP supported by riverine nutrients may be slight, the impact of the organic carbon supplied by rivers on ocean-atmosphere

CO_2 fluxes can be quite prominent, particularly on interior shelves in the Eurasian Arctic sector where a significant fraction of Arctic Ocean riverine discharge takes place (Anderson et al., 2009; Frey and McClelland, 2009; Pipko et al., 2017). Remineralization of allochthonous organic matter increases $pCO_{2\ w}$, while turbidity associated with increased particle load lowers light penetration and dampens primary productivity (**Figure 4**; Carmack et al., 2006). These processes are reflected in a gradient toward increasing $pCO_{2\ w}$ from west to east across the Eurasian shelves, with low $pCO_{2\ w}$ in the Barents Sea driven by cooling of Atlantic water and high productivity rates and increasingly high $pCO_{2\ w}$ toward the eastern Siberian Seas where stratification-induced warming of surface waters, high $pCO_{2\ w}$ in river discharge, and high rates of terrestrial organic matter remineralization dominate (Anderson et al., 2009; Pipko et al., 2017). The East Siberian Seas still represent a sink for CO_2 but are prone to periods of outgassing; it might be expected that with increased mobilization of permafrost and continued warming, these areas might become a more reliable source of CO_2 in the future (Anderson et al., 2009). More generally, enhanced stratification from increased surface temperatures and increased river discharge may reduce CO_2 uptake capacity on Eurasian interior shelves, although this stratification increase may be countered by increased storm-induced-mixing (Pipko et al., 2017).

Another important trend in this region is a significant increase in alkalinity exported to the Arctic Ocean from the Yenisei and Ob' Rivers; between 1974 and 2015, alkalinity export by these two rivers more than doubled (from 225 to 642 Geq yr^{-1} and from 201 to 470 Geq yr^{-1} for the Yenisei and Ob', respectively; Drake et al., 2018). Proposed drivers of this increase include increased temperature, deepening of the permafrost active layer, and longer contact time with unweathered mineral surfaces. If similar increases in alkalinity export apply for the two other large Eurasian rivers (Lena and Kolyma), the increase in Arctic Ocean alkalinity has the potential to enhance CO_2 sequestration by 3.4 Tg yr^{-1} (120 Tg C over 1974–2015; Drake et al., 2018). This increase is of the same magnitude as the compiled estimates of regional CO_2 uptake in the Kara, Laptev, and East Siberian Seas, which range from 1 Tg C yr^{-1} to 6 Tg C yr^{-1} (Bates and Mathis, 2009); hence, increased buffering capacity will be an important determinant of future CO_2 uptake in this region.

CONCLUSIONS

Changes in the biogeochemical cycling of nutrients through Arctic Ocean subregions are inevitable as aspects of the physical system change. DIN availability might increase due to advected inputs at inflow regions, increase due to reduced ice conditions coupled with enhanced storm activity (shelf break upwelling or storm-induced mixing), or decrease as source waters change or stratification limits seasonal replenishment. Hence, there is no single, unified trajectory for Arctic Ocean biogeochemical change—rather, profound regional differences shape a mosaic of trends and outcomes. Changes to nutrient availability already seem to be driving changes in Arctic Ocean PP (Lewis et al., 2020; Terhaar et al., 2021), but what is less clear is the extent to which these trends are driven by new or regenerated production. This new/regenerated distinction has important implications for understanding future changes in Arctic ecosystems, trophic transfers, pelagic-benthic coupling, and capacity for biologically mediated air-sea CO_2 exchange.

Given the variety of individual regional responses, observations and modeling are both critical needs for tracking the shifting baselines of Arctic Ocean biogeochemical change, the mechanisms driving them, and implications for the future. Observations must be collected at appropriate spatiotemporal scales to resolve processes of interest; however, this is challenging given the importance of event-driven features (storms) and the need for measurements outside of the easily accessible open water period (to assess seasonal nutrient replenishment trends). Models will also need to adequately resolve mixing processes and their responses in shallow coastal environments and deep basins alike. Finally, given the interwoven functioning of Arctic Ocean physical, biogeochemical, and ecological systems, our ability to understand and predict future change hinges on interdisciplinary coordination from measurement to synthesis.

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SIDEBAR > ALASKAN SEABIRD DIE-OFFS

By Robb Kaler and Kathy Kuletz

Prior to 2015, seabird die-offs in Alaskan waters (Northern Gulf of Alaska, eastern Bering Sea, eastern Chukchi Sea) were rare, typically occurred in mid-winter, and were linked to epizootic disease events (Bodenstein et al., 2015) or above-average ocean temperatures associated with strong El Niño-Southern Oscillation events. An example was late summer of 1997, a year with unusually warm waters in the southeastern Bering Sea, when possibly as many as 10% of the several million short-tailed shearwaters (*Ardenna tenuitortris*) present in the area died of starvation because their principal prey, euphausiids, were scarce or hard to find in a widespread coccolithophore bloom (Baduini et al., 2001). Since 2015, similar or smaller mass mortality events have been annual occurrences. In 2015, between 470,000 and 1.03 million common murres (*Uria aalge*) were estimated to have died in the Gulf of Alaska due to anomalous ocean conditions and the impacts on forage fish associated with the 2014–2016 Pacific marine heatwave (Piatt et al., 2020; Arimitsu et al., 2021). Another large die-off event occurred during late summer of 2019 (Figure 1), when over 10,000 carcasses of short-tailed shearwaters washed onto beaches of Bristol Bay and the Alaska Peninsula in the southeastern Bering Sea. Total mortality during that summer was likely much greater than reported given the region's expansive coastline and sparse human population.

Seabirds are natural indicators of the status of marine ecosystems, and since at least 2017, die-offs in the northern Bering and southern Chukchi Seas (including some reports from the Russia Far East) have been concurrent with massive ecological shifts resulting from increased ocean temperatures coupled with decreased duration and extent of sea ice in those seas. Changes include a decrease in the large crustacean zooplankton that support planktivorous seabirds (Duffy-Anderson et al., 2019). In addition, there has been significant reduction of the cold pool thermal barrier, a layer of ≤2°C water near the seafloor that restricts species like Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Gadus chalcogrammus*) from entering the northern Bering Sea. More recent studies in the Pacific Arctic region indicate the northward movement of adult cod and pollock (Duffy-Anderson et al., 2019; Eisner et al., 2020) that might compete with seabirds for food.

Seabird species affected since 2017 in eastern Bering and Chukchi Seas include planktivorous birds such as auklets (*Aethia* spp.) and shearwaters, piscivorous murres, puffins (*Fratercula* spp.), and kittiwakes (*Rissa* spp.), as well as some benthic-feeding sea ducks (*Somateria* spp.). Involvement of a range of seabird species that consume different prey, and localized mortality events throughout summer across a vast region (albeit with relatively low numbers at individual

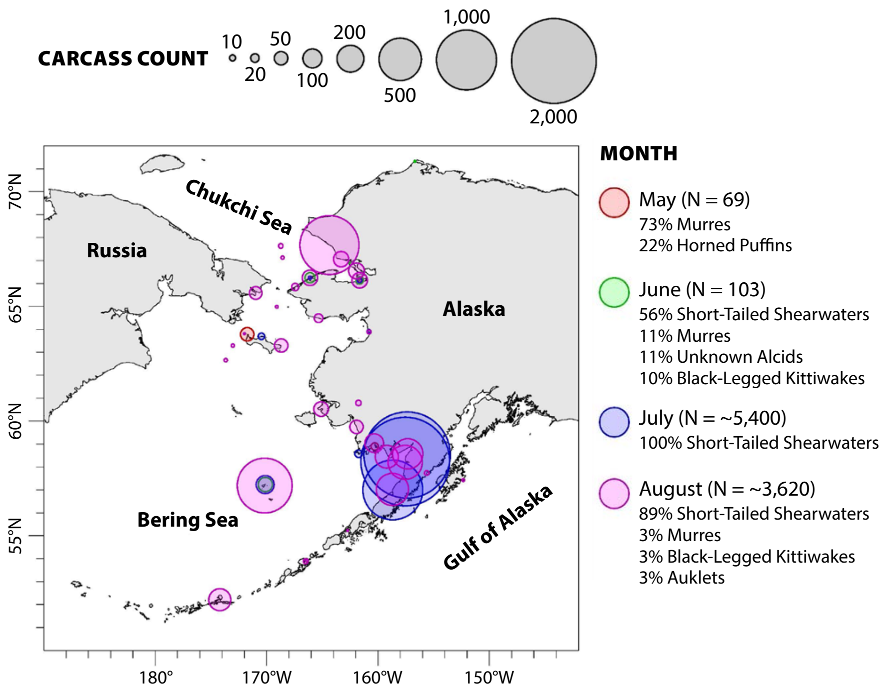

FIGURE 1. Location and number of seabird carcasses reported in Alaska during 2019. Data compilation and map were provided by the Coastal Observation and Seabird Survey Team (COASST; University of Washington, Seattle), and relied on data collected by community members, Alaska Sea Grant, the US National Park Service, and the US Fish and Wildlife Service.

sites), signal broadscale, ecosystem-level impacts at multiple trophic levels. Such wildlife mortality events are of concern not only for coastal communities that rely on ocean resources for their nutritional, cultural, and economic well-being but also signal concern for the state of subarctic and Arctic oceans.

While starvation has been identified as the main cause of death for carcasses examined by US Geological Survey (USGS) National Wildlife Health Center scientists, university and federal researchers continue to evaluate other possible contributing factors. To date, highly pathogenic diseases have not been detected in tested carcasses. Exposure to saxitoxin, associated with harmful algal blooms, was detected in seabird tissues in 2017; however, direct neurotoxic results from saxitoxin could not be confirmed, and starvation appeared to be the proximate cause of death among birds examined (Van Hemert et al., 2021). USGS researchers at the Alaska Science Center continue to investigate algal toxins in marine invertebrates and forage fish and are conducting experimental trials to determine effects of saxitoxin on seabird behavior and health, which may include emaciation.

With seabird mortalities reported over a wide geographic region and throughout summer and fall on an annual basis, how are birds doing at breeding colonies? Observations at northern seabird breeding colonies indicate lack of breeding attempts or very late and unsuccessful breeding between 2017 and 2019 (Romano et al., 2020; Will et al., 2020). Although these observations suggest that the seabird die-offs stem from multiple ecosystem changes associated with abnormally high ocean temperatures, including forage fish quantity and quality, unfavorable foraging conditions (competition with fish), or exposure to harmful algal bloom biotoxins, there still is no confirmed “smoking gun.”

The bottom-up effects linked with changes in the prey base and top-down effects associated with increased metabolic rate, along with food demands of competing fish species that could reduce prey availability to seabirds and marine mammals, is referred to as an “ectothermic vise” by Piatt et al. (2020). With increasing ocean temperatures and decreasing sea ice, the next decade will be critical for upper trophic organisms and human communities adapting to a fast-changing environment in northern Alaska.

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

By Kathleen M. Stafford, Edward V. Farley, Megan Ferguson, Kathy J. Kuletz, and Robert Levine

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

Two transient killer whales in the Chukchi Sea in September 2017. *Image credit: K.M. Stafford*

INTRODUCTION

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

While climate change is altering the entire Arctic, not every region in the highly heterogeneous Arctic is equally affected (e.g., Moore et al., 2019; Polyakov et al., 2020; Mueter et al., 2021a). In the Atlantic, there are two wide, deep, high-latitude gateways to the Arctic: Davis Strait (300–900 km wide) and Fram Strait/Barents Sea (~450 km wide). The sole gateway to the Pacific Arctic is through the narrow Bering Strait (80 km), south of the broad, shallow Chukchi Sea shelf (Figure 1). Observed differences between the Atlantic and Pacific Arctic regions include a much greater increase in the open water season in the Barents Sea than in the Chukchi Sea, and differences in water mass composition and advection of heat and nutrients, all of which shape ecosystem structure (Hunt et al., 2013; Oziel et al., 2017).

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

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

MARINE FISHES

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

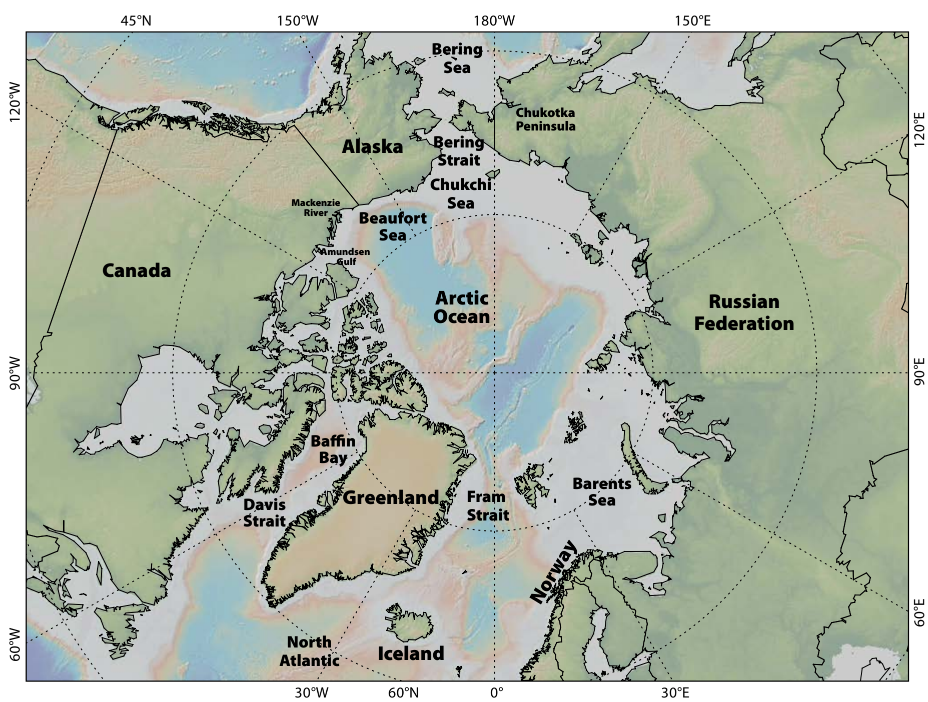

FIGURE 1. Map of the Arctic showing major gateways and waterways. Map made with GeoMapApp (http://www.geomapapp.org/; Ryan et al., 2009).

generalist boreal fishes are likely to outcompete the specialist diets of Arctic species (Kortsch et al., 2015).

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

Walleye Pollock

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

FIGURE 2. Historic and recent observations of walleye pollock distributions in the Bering and Chukchi Seas. Recent warming has led to a northward shift of the population in the Bering Sea (approximate distributions from Eisner et al., 2020), and surveys have reported large pollock populations in the eastern (juvenile only; recent work of author Levine) and western (adult and juvenile; Orlov et al., 2020) Chukchi Sea.

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

Juvenile pollock growth rates exceed those of other gadid species under the warm conditions of the Arctic summer (Laurel et al., 2016), potentially allowing them to outcompete Arctic species; however, their hatch and survival rates are reduced under the seasonal freezing conditions (Laurel et al., 2018).

Thus, while the substantial increase in juvenile pollock in the Pacific Arctic suggests that environmental conditions now allow pollock to extend into the Chukchi Sea on a seasonal basis, their ability to establish permanent populations in the Arctic remains unknown.

Pink Salmon

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

SEABIRDS

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

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

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

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

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

CETACEANS

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

Killer Whales

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

The northward range expansion, longer seasonal presence, and higher numbers of a top predator in the Arctic has the potential for top-down ecosystem reorganization and may represent the most immediate threat to Arctic endemic species (S.H. Ferguson et al., 2010). In the eastern Canadian Arctic, endemic narwhals, belugas, and bowhead whales

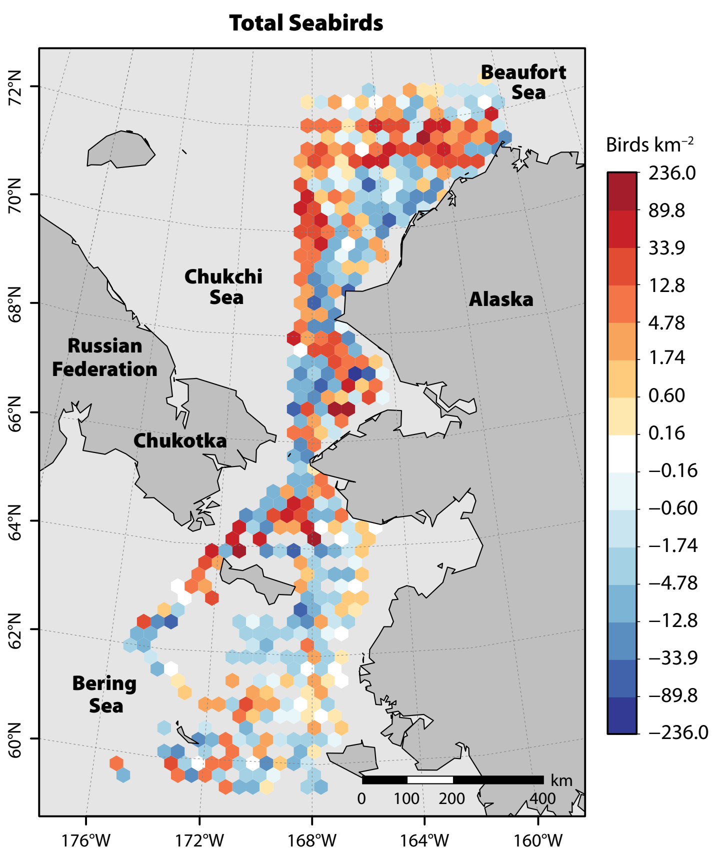

FIGURE 3. Distribution changes in the Pacific Arctic region for total seabird densities (birds km^{-2}) during 2017–2019 compared to the previous decade. Cells with increasing (orange) and decreasing (blue) densities during 2017–2019 were based on mean densities of all observations within each 50 km grid cell. *Adapted from Kuletz et al. (2020)*

change their behavior in the presence of killer whales (reviewed in Matthews et al., 2020). Lefort et al. (2020) suggest that this species could have a significant negative impact on narwhal populations in the Canadian Arctic Archipelago.

Subarctic Baleen Whales

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

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

CONCLUDING THOUGHTS

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

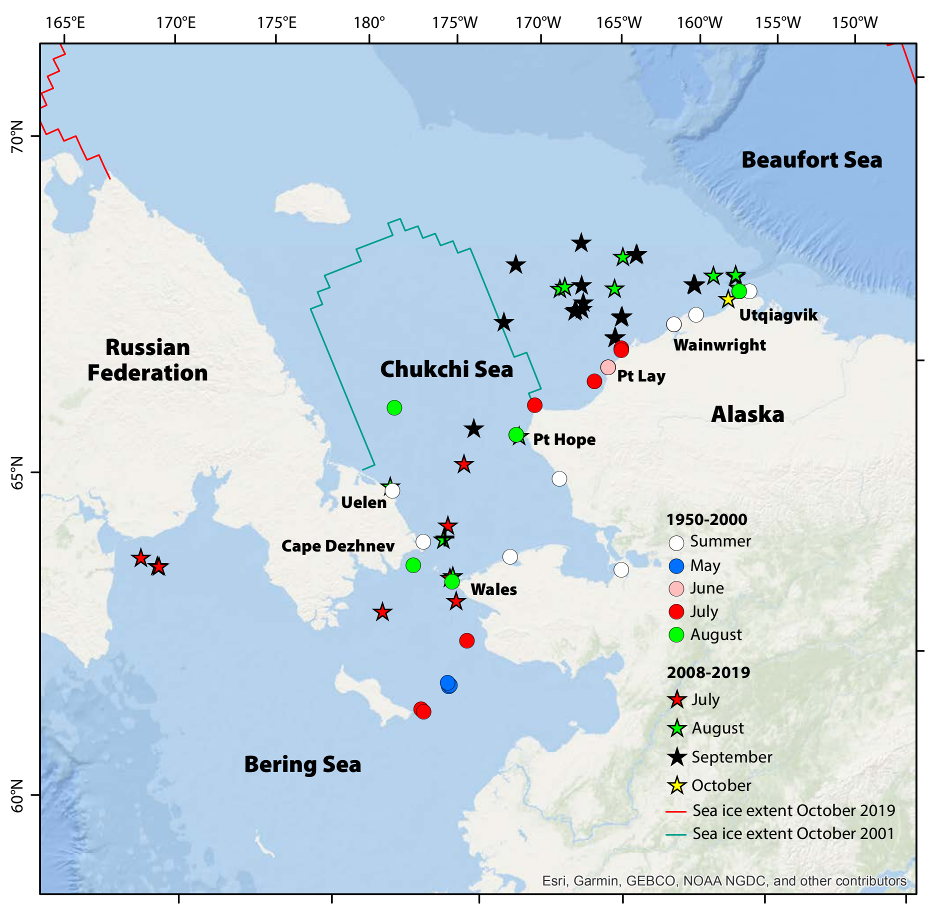

FIGURE 4. Killer whale sightings in the Pacific Arctic by month from 1950 to 2000 (circles) and 2008 to 2019 (stars). Sea ice extent is shown for October 2001 (blue line) and 2020 (red line). *Adapted from Stafford (2019)*

competition for prey, novel predators, and exposure to novel pathogens will be critical (e.g., Post et al., 2013; Kortsch et al., 2015; VanWormer et al., 2019). The evidence we summarize here indicates large-scale shuffling of subarctic and Arctic marine animal communities as high-latitude marine ecosystems undergo rapid reorganization.

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STRATEGY FOR PROTECTING THE FUTURE ARCTIC OCEAN

By Lawson W. Brigham and James T. Gamble

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ABSTRACT. Marine access in the Arctic Ocean is increasing due to the relentless retreat of sea ice driven by anthropogenic climate change. Longer seasons of marine navigation allow increasing marine use by a diversity of stakeholders and vessels. Progress has been made in protecting the Arctic Ocean through cooperation among the Arctic states and proactive advances within international organizations, notably the International Maritime Organization. Measures addressing Arctic marine safety and environmental protection have been developed and adopted. This paper reviews 12 strategic goals or pathways forward for implementing policy measures developed in an array of organizations to protect the future Arctic Ocean. Ten high-priority recommendations, all near-term action items that are believed achievable, are also advanced toward protecting Arctic people and the marine environment in the twenty-first century.

INTRODUCTION

The Arctic is undergoing many environmental, social, economic, and security changes. Marine access in all seasons is increasing due to the profound retreat of Arctic sea ice driven by anthropogenic climate change, and potentially longer seasons of marine navigation are emerging (Figure 1). Recognizing new and increasing Arctic marine traffic during the past three decades, the eight Arctic states (Canada, Denmark [Greenland], Finland, Iceland, Norway, Sweden, the Russian Federation, and the United States) and international organizations have been proactive in addressing the many challenges and requirements for improved Arctic marine safety and marine environmental protection. Assessments by the Arctic Council (on climate change, shipping, human development, oil and gas, and biodiversity), a new mandatory code of rules and regulations for ships sailing in polar waters (the "Polar Code"; Box 1; IMO, 2017), and key Arctic state treaties have all contributed to significant advances in protection of the Arctic and broad cooperation in the region (see the first three "Agreement" listings among the references for Cooperation on SAR, 2011; Cooperation on Oil Pollution, 2013; and Scientific Cooperation, 2017).

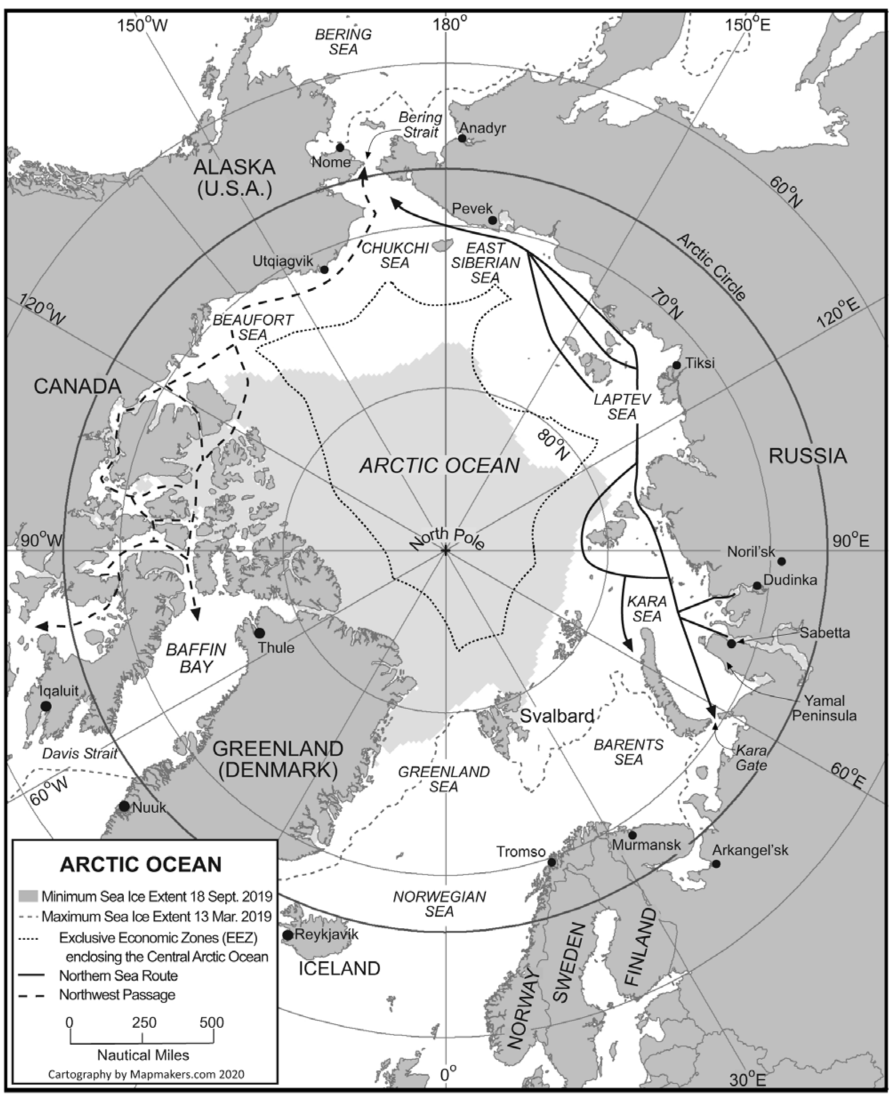

FIGURE 1. The dotted line on this map indicates the outer limits of the Exclusive Economic Zones of the five Arctic Ocean coastal states and defines the area of the high seas or the Central Arctic Ocean. Marine distances here can be long—more than 2,000 nautical miles from Bering Strait through the North Pole and out to Fram Strait between Greenland and Svalbard, and nearly 3,000 nautical miles along the Russian maritime Arctic and the Northeast Passage (the Northern Sea Route does not include the Barents Sea) from Pacific to Atlantic Oceans.

However, much more is required: continued implementation of existing measures, more ocean and climate research, development of new and more integrated policy approaches, and expanded infrastructure investment.

The Arctic Council's Arctic Marine Shipping Assessment (AMSA), conducted by the Council's Protection of the Arctic Marine Environment Working Group, set the tone for Arctic Ocean protection when it was released in April 2009 (Arctic Council, 2009). It was the first comprehensive and integrated review focused on protection of Arctic people and the marine environment in an era of increasing use of the Arctic Ocean. Approved by the Council's eight foreign ministers, AMSA remains a baseline assessment of Arctic marine activity and a historic snapshot of Arctic marine use early in the twenty-first century. It offers a strategic guide for a host of maritime states, Indigenous groups, marine operators, and a multitude of stakeholders and actors. Most importantly, taken together, AMSA's recommendations represent a policy framework for the Arctic states.

This paper identifies 12 key strategic goals or pathways forward for using policy measures to protect the future Arctic Ocean. These strategic goals are interrelated and are consistent with AMSA's three, over-arching themes: Enhancing Marine Safety, Protecting Arctic People and the Environment, and Building the Arctic Marine Infrastructure (Arctic Council, 2009). Table 1 provides AMSA's three main themes and 17 topical recommendations. Only by using holistic, integrated approaches can effective progress be made in advancing Arctic marine safety and marine environmental protection. Each of these strategic goals will require broad cooperation among the eight Arctic states and within such organizations as the International Maritime Organization (IMO), the International Hydrographic Organization (IHO), the World Meteorological Organization (WMO), and the International Whaling Commission (IWC).

STRATEGIC GOAL 1: IMO POLAR CODE IMPLEMENTATION AND ENFORCEMENT

Expanding and enhancing the implementation and enforcement of the IMO Polar Code present the Arctic and flag states with many practical challenges for all polar capable ships. For the many flag states involved (most outside the Arctic), the ship classification societies are at the forefront of providing expert technical guidance on ship construction and safety equipment components as well as issuance of a Polar Certificate and a Polar Water Operational Manual under the Polar Code (IMO, 2017). The societies continue to work closely with the flag states in order to provide significant uniformity in how the Polar Code is implemented. For the Arctic states, development and negotiation of an Arctic Port State Control Agreement would be a practical way to enhance effective and harmonized enforcement of the Polar Code. Such an agreement would surely require improved sharing of Arctic marine traffic information among the partners so that each Arctic state would have advance knowledge of ships sailing north to Arctic waters and along established routes. Likely, the Russian Federation would be the only Arctic state concerned about the release (from state to state) of traffic data in a real-time format. However, prior to Russia' invasion of Ukraine, Russian maritime experts had been open to discussing port state control as a mechanism for improving enforcement of the Polar Code. Future expanded Arctic marine traffic, especially if fishing vessels might be included under the Code, may require a more tightly managed system, with coordinated port state oversight and control of vessels sailing in and out of the Polar Code Arctic area.

The Polar Code came into force five years ago and is now due for a systematic

TABLE 1. The Arctic Council's Arctic Marine Shipping Assessment (AMSA) Themes and Topical Recommendations*

THEME I. ENHANCING ARCTIC MARINE SAFETY

- Linking with International Organizations
- IMO Measures for Arctic Shipping
- Uniformity of Arctic Shipping Governance
- Strengthening Passenger Ship Safety in Arctic Waters
- Arctic Search and Rescue (SAR) Agreement (Implement Treaty)

THEME II. PROTECTING ARCTIC PEOPLE AND THE ENVIRONMENT

- Survey of Arctic Indigenous Marine Use
- Engagement with Arctic Communities
- Areas of Heightened Ecological and Cultural Significance
- Specially Designated Arctic Marine Areas
- Protection from Invasive Species
- Oil Spill Prevention
- Addressing Impacts on Marine Mammals, Seabirds, Fish, and other Marine Life
- Reducing Air Emissions

THEME III. BUILDING THE ARCTIC MARINE INFRASTRUCTURE

- Addressing the Infrastructure Deficit
- Arctic Marine Traffic System
- Circumpolar Environmental Response Capacity (Implement Treaty)
- Investing in Hydrographic, Meteorological, and Oceanographic Data

*AMSA Report (April 2009) and AMSA Updated Recommendations by the Protection of the Arctic Marine Environment Working Group (PAME) (May 2021).

BOX 1. GUIDE TO THE INTERNATIONAL MARITIME ORGANIZATION CODE FOR SHIPS OPERATING IN POLAR WATERS (IMO POLAR CODE)

The IMO Polar Code is a relatively new governance regime for polar waters that addresses marine safety and environmental protection challenges for ships operating in the remote and sometimes extreme conditions of the Arctic and Southern Oceans. The Polar Code entered into force initially on January 1, 2017, and mariner certificate and training requirements were mandated on July 1, 2018. The elements of the Polar Code are amendments to three existing IMO conventions: the International Convention for the Safety of Life at Sea (SOLAS), the International Convention for the Prevention of Pollution from Ships (MARPOL), and the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW).

The Polar Code includes new mandatory requirements for ships operating in polar waters, regarding:

- Ship structural and construction standards for Polar Class ships
- Marine safety and life-saving equipment designed for operation in polar environments
- Training and experience of the ships' officers and crew
- Environmental rules regarding the discharge of oil, noxious liquids, sewage, and garbage
- A Polar Ship Certificate issued by the flag state administration or an authorized representative such as a ship classification society
- An onboard Polar Water Operational Manual unique to a given ship that includes operational capabilities and imitations

The Polar Code is applicable to all commercial carriers and passenger vessels on international voyages that are 500 gross tons or greater. Fishing vessels, small cargo ships, and yachts are not currently under the Code. The Polar Ship Certificate classifies each ship under the Code into one of three types:

- Category A: Ships designed for operation in polar waters in at least medium first-year ice that may have old ice inclusions;
- Category B: Ships for operations in polar waters in at least thin first-year ice that may have old ice inclusions;
- Category C: Ships designed for operations in open water or in ice conditions less severe than those in Categories A and B.

The third category was necessary because Arctic summer ship traffic now includes many vessels, such as large passenger cruise ships, that have been operating in waters that are generally ice-free. The lack of infrastructure available for emergency response and lack of hydrographic information for modern charts pose significant risks and challenges for these vessels. Thus, they must meet the Polar Code's higher standards of marine safety equipment and requirements for mariner training and experience.

The Polar Code boundary in the Southern Ocean around Antarctica is 60°S, corresponding to the northern boundary of the Antarctic Treaty. The Polar Code boundary in Arctic waters is more complex: in the Bering Sea, the boundary is set at 60°N as one measure to protect the region's large fishery, which closely follows the seasonal maximum of winter sea ice extent; in the Atlantic, the boundary adjusts to warmer North Atlantic waters, running south of Greenland and then northeast along the East Greenland coast, north of Iceland, and then intersecting with the Russian coast in the Barents Sea.

The IMO Polar Code should be viewed as a seminal advance in international governance of polar waters. The Code's coverage is broad, mandating operational equipment; defining ship design and construction requirements; addressing specific criteria for operations, manning, and training; prohibiting discharges of oil and noxious liquids in Arctic waters; and mandating controls on the discharge of sewage and garbage in Arctic waters. However, it is a work in progress, a living regulatory instrument, and only the beginning of a long-term effort to protect the Arctic Ocean and its inhabitants.

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review and gap analysis in order to identify successes and problems. Although it is unlikely the Arctic states could conduct such a review today, select classification societies along with perhaps a nongovernmental organization could be contracted to perform this important work. Significant data and other information (e.g., on national implementation and enforcement processes) would be required from marine operators and the Arctic states to ensure comprehensive and accurate analyses.

Enforcing the diverse elements of the Polar Code is challenging, but the very nature of its complexity and the roles of many maritime states and organizations in the compliance and enforcement process may dictate its success. The primary responsibility for compliance and enforcement rests with the flag states and in some circumstances falls to the Arctic port states. The ship classification societies are influential in certifying that existing and new ships meet Polar Code rules, and the marine insurance industry has a clear role in ensuring only ships that meet new polar standards regarding construction, safety equipment, and manning. Monitoring and tracking of commercial ships operating in Arctic waters to ensure compliance with broad environmental security requirements, including enforcement of the Polar Code, will take on increasing importance.

STRATEGIC GOAL 2: EXPANSION OF VESSELS INCLUDED UNDER THE IMO POLAR CODE

The IMO Polar Code was designed initially to address large commercial ships (500 gross tons or more) operating in polar waters, including cargo carriers (such as container ships, gas transports, oil tankers, and bulk carriers) and large passenger vessels, specifically those of the global cruise ship industry that are designated Category C in the Polar Code. Government civilian and naval ships of all types and tonnages (such as icebreakers, hydrographic ships, and survey vessels) are exempt from the Polar Code (IMO, 2017). One of the challenges and limitations of the Code is that it currently does not include fishing vessels, small cargo ships, pleasure craft, and yachts. These vessels are referred to as “non-SOLAS” class, and they generally operate outside the main marine safety and environmental protection regulations mandated for larger vessels.

Past surveys by the Arctic Council and others have indicated that fishing vessels represent the largest population of vessel types using the Arctic Ocean (Arctic Council, 2009). With greater marine access in Arctic coastal waters and in the high seas (the Central Arctic Ocean), and potentially longer fishing seasons in higher latitudes, there is concern for the safety of these smaller vessels and their crews as well as their cumulative discharges of sewage and wastes, air emissions, and plastics from fishing nets and other equipment. The Maritime Safety Committee of the IMO has finalized measures for expanding the Polar Code to include fishing vessels of 24 meters and greater in Arctic waters (WWF, 2022). The Code would also include small cargo vessels and pleasure yachts of 300 gross tons and above. The coastal states with large deep-water fishing fleets will have some concerns due to their historic links to (and control within) the industry and new responsibilities as flag states for implementing and enforcing the Polar Code for a much larger number of vessels. Several of the more challenging tasks for the Arctic coastal states will be effective monitoring and surveillance of these fishing vessels and enforcing the Polar Code along with applicable national fisheries management regulations.

STRATEGIC GOAL 3: ARCTIC SHIP EMISSIONS AND HEAVY FUEL OIL

Although vessel emissions and discharges present a global pollution problem, some are especially critical in the Arctic and require special efforts through both international regulation and voluntary measures. The most common shipping fuel, heavy fuel oil, or HFO, is what remains after almost everything possible has been distilled from crude oil. HFO is very difficult to clean up when spilled, and this is particularly the case in cold water where low temperatures and the presence of ice make the use of traditional oil spill clean-up equipment, such as containment booms, skimmers, and absorbents, difficult if not impossible (Det Norske Veritas, 2011). The risk that a spill of HFO in cold water represents is so extreme that the 2009 AMSA report listed an HFO spill as the single greatest threat to the Arctic marine environment from shipping (Arctic Council, 2009). In addition, the risk of a cold water HFO spill led the IMO to ban its use and carriage in Antarctic waters in 2011 (IMO Annex I Amendment 2011). The IMO has also adopted a ban for HFO in Arctic waters (IMO, PPR7/22/Add. 1: Annex 12) that will enter into force in 2024, but with exemptions for certain vessel types, and waivers that can be granted by an Arctic flag state to ships traveling in Arctic waters under their own flag. The ban will only reduce the amount of HFO used in the Arctic by about 16% until 2029 (Comer et al., 2020), when the ability for the Arctic states to grant waivers expires. The need to transition away from the use of HFO as fuel in Arctic waters more quickly is critical enough that 12 nations signed a resolution that was adopted by the IMO in November 2021 calling for an immediate, voluntary switch to cleaner distillate fuels for vessels traveling in Arctic and near Arctic waters (IMO, Resolution MEPC.342 (77)).

A particularly significant consequence of ships burning HFO is that a common pollutant found in the exhaust is black carbon or soot (ICCT, 2016). A component of PM2.5, black carbon is a result of incomplete combustion of fossil fuels, biofuels, and biomass. For the Arctic, black carbon presents a particularly urgent problem, as it not only warms the atmosphere while in the air but also results in accelerated melting of snow and ice when it settles on these cold, white surfaces. This means that black carbon is a very significant driver of climate change (Bond, 2013), second only to CO_2—and ships traveling in or near the Arctic bring black carbon to the very place that is the most sensitive. Black carbon also presents a substantial risk to human health (Janssen, 2012; DeCola et al., 2018), and even remote places may be exposed to this risk if they lie along shipping routes.

Arctic countries, and others with Arctic interests, should pursue an immediate transition away from HFO to cleaner distillate fuels in Arctic waters. This will have the dual benefit of lessening the risk of a devastating oil spill and very significantly reducing emissions of black carbon from ships in the Arctic.

STRATEGIC GOAL 4: MARINE PROTECTED AREAS

Marine protected areas (MPAs), which restrict human activities for the purpose of conservation, not only protect specific areas that have been found to be especially sensitive, important to biological productivity, or vital to the subsistence and/or cultural practices of Indigenous peoples but also help to protect biodiversity. And they provide a place for scientists and the public to observe nature in an undisturbed state. Currently, the United Nations Convention on Biodiversity is leading a process to develop a new Global Biodiversity Framework, with a likely goal of protecting 30% of our planet by 2030, usually referred to as 30×30. This goal seems to be largely supported by the Arctic states, and it provides an excellent opportunity to identify and create new MPAs for sensitive and valuable Arctic marine areas.

Terrestrial protected areas were well represented as of 2019, with over 1,000 divided among the permafrost region in the eight Arctic states. However, MPAs are very underrepresented, with only about 60 that do not include a coastal component Arctic wide (IUCN and UNEP-WCMC, 2019). This highlights the need for more science and assessment of Arctic marine areas to determine those that are important for protection. Working within the Arctic Council's Protection of the Arctic Marine Environment (PAME) Working Group, a Marine Protected Area Expert Group has focused on assessing the state of important Arctic protected areas and has produced an MPA Network Toolbox (Arctic Council, 2017). Their findings show that while the Arctic states have established several MPAs, there are still many gaps to be filled.

With the extreme pressure on Arctic ecosystems being brought about by climate change, and increasing economic development activities, a harmonized approach to existing MPA management is vital. The development of new MPAs must be oriented toward protecting a diversity of Arctic flora and fauna and the ecosystem services that they provide. In addition, there should be a formalized understanding of Arctic MPAs as "no dumping" zones, which would be an essential step toward protecting these areas from shipping pollution. Finally, the Arctic states should urgently support 30×30, especially in Arctic waters, and proceed with the research, inclusion of Indigenous knowledge (IK), and involvement of Indigenous leaders necessary to identifying and implementing MPAs in the region. A recent US definition of ITEK, or Indigenous Traditional Ecological Knowledge, is applicable: "a body of observations, oral and written knowledge, practices and beliefs that promote sustainability and the responsible stewardship of natural resources through relationships between humans and environmental systems" (White House, 2021).

STRATEGIC GOAL 5: SURVEYS OF INDIGENOUS ARCTIC MARINE USE

Organizations such as the Arctic Council have long recognized the need to conduct comprehensive surveys of Indigenous marine use in all sovereign waters of the Arctic coastal states. The objective is to integrate IK with what is often referred to as "Western science" within the national surveys to create a holistic map of Arctic Ocean Indigenous marine use. Such a map would be used to assess the impacts (seasonal and year-round) of regional marine operations and potential trans-boundary shipping routes. This would allow an evaluation of the potential impacts on food and cultural security for Arctic coastal communities. A comprehensive survey of this type was a key recommendation of the 2009 AMSA report, which also called on Arctic states to identify areas of heightened ecological and cultural significance. The most comprehensive effort provided a partial picture of cultural and subsistence use areas in a report published in 2013 by the Arctic Monitoring and Assessment Programme (AMAP) working group, the Conservation of Arctic Flora and Fauna (CAFF) working group, and the Sustainable Development Working Group (SDWG) of the Arctic Council along with the Permanent Participants' Aleut International Association and the Saami Council (AMAP/CAFF/SDWG, 2013).

The best scenario for a comprehensive survey of this nature is likely an effort to be led by one or more Arctic Indigenous organizations, such as those within the Arctic Council Permanent Participants. Both the Inuit Circumpolar Council (ICC) and the Saami Council have constituencies that span multiple Arctic states and have extensive experience working with a variety of international institutions; for example, the ICC became the first Indigenous organization with Consultative Status at the IMO in November of 2021 (ICC, 2021). Finally, it will be crucial that the Arctic states provide the needed resources for a truly comprehensive survey of areas of importance for subsistence use and cultural significance.

STRATEGIC GOAL 6: ECOSYSTEMS-BASED MANAGEMENT AND INDIGENOUS KNOWLEDGE

Arctic Indigenous peoples have lived and depended on Arctic lands and waters for many millennia, developing a special knowledge of place that is passed from generation to generation. Indigenous knowledge has provided valuable insights into a variety of Arctic topics such as the health and status of ecosystems, changes in weather patterns, variability in species migration, and many more. IK and Western science complement each other and should be considered equally in Arctic research. Accomplishing this may require extra time on a project to ensure the participation of all stakeholders.

The Arctic Council definition of ecosystem-based management (EBM) describes it as "the comprehensive, integrated management of human activities based on the best available scientific and traditional knowledge about the ecosystem and its dynamics, in order to identify and take action on influences that are critical to the health of ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity" (Arctic Council, 2013). Put more simply, it is a system for managing human activities that considers the entire ecosystem, including humans, in decision-making. EBM doesn't focus on deliverables, such as maximizing productivity of a few species, but instead focuses on long-term sustainability as the goal. Most marine area management systems make use of at least some of the principles of EBM, such as using the best available science and IK to assess the state of the ecosystem, identifying current and possible future stressors, enabling full participation by all stakeholders, assessing potential economic and ecological trade-offs, setting goals with long term sustainability in mind, and evaluating management measures to assess their effectiveness on a regular basis. However, these efforts often fall short due to a lack of resources and/or commitment.

In the Arctic there is an opportunity to "do it right" by combining IK and Western science to gather much needed data to answer questions about the region, and then using the principles of EBM to analyze, prioritize, and manage human activities to ensure sustainability. "Doing it right" also means that Arctic research and policy must make it happen with robust cross-border cooperation among all stakeholders, sufficient resources, and striving to collaborate fully with Indigenous peoples to holistically include IK at all levels of the EBM process.

STRATEGIC GOAL 7: INTEGRATED ARCTIC OBSERVING NETWORK

Despite a long and notable history of Arctic exploration and observations, the fact remains that records for the region are very incomplete, with major gaps in nearly all disciplines. The reasons for this are obvious: the region is remote, and the Arctic environment is challenging for both people and equipment. Thus, exploration and observations are more resource intensive than in other regions of the planet. Consistent, long-term observations are especially challenging; consequently, significant time series are lacking. By its very nature, the Arctic is an area of international interest, not only for the eight countries that border the Arctic but also for a host of other nations that recognize the important relationship of the Arctic to the entire planet. This makes the Arctic a natural place for an integrated observing network that utilizes the resources of many contributors, both public and private.

Efforts along these lines are underway, as exemplified by Danielson et al. (2022, in this issue), Lee et al. (2022, in this issue), and others. Development and maintenance of a robust Integrated Arctic Observing Network (IAON) as a fundamental part of Arctic infrastructure will be essential to understanding the profound impacts of climate change and increasing human activity in the Arctic. In addition, a well-functioning IAON will greatly enhance maritime safety and environmental protection by supporting governance regimes such as the IMO Polar Code and by providing critical, real-time information to Arctic marine operations. An IAON will also be crucial to the research needs of the Central Arctic Ocean Fishing Agreement (discussed below).

It should be noted that there are institutions well poised to mobilize a new IAON, such as the International Arctic Science Committee (IASC), a nongovernmental organization established to encourage, facilitate, and promote cooperation in Arctic research, and Sustaining Arctic Observing Networks (SAON; Chythlook et al., 2022, in this issue), a joint activity of IASC and the Arctic Council organized to enhance Arctic-wide observing activities. It is important that the Arctic states in partnership with Indigenous organizations and other stakeholders work to develop enhanced observing networks by providing the necessary resources and ensuring that data gathered is made freely available to users in as near-real time as possible. It is also crucial that recommendations to policymakers realized from integrated observing be as robust and specific as possible to provide enhanced decision-making.

STRATEGIC GOAL 8: CENTRAL ARCTIC OCEAN FISHERIES AGREEMENT

The Central Arctic Ocean Fisheries Agreement is a groundbreaking example of the precautionary principle put effectively into practice. Signatories are Canada, China, Denmark (in respect to Greenland and the Faroe Islands), the European Union, Iceland, Japan, Norway, the Russian Federation, the Republic of Korea, and the United States (Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, 2021). The agreement, which entered into force on June 25, 2021, is designed to prevent unregulated fishing in the area of the Arctic Ocean beyond national jurisdiction and to promote joint research and monitoring in this remote region. Representing both challenge and opportunity, the agreement commits the signatories to disallowing commercial fishing in the area for at least 16 years, and to gathering much needed information about the Central Arctic Ocean ecosystem during that time. This is a marked departure from the way that commercial fishing typically happens, where fishing interests exploit new fish stocks, and then seek to determine how these fish fit into the ecosystem and what level of fishing is required to attain sustainability, often after the stocks have crashed, or some other event points to a problem. Unfortunately, the results of this approach are often very negative, and there are areas where, even after decades, fish stocks have not recovered from overfishing.

The CAO agreement provides the opportunity to gather information about the region by prioritizing both Western science and IK, and then to manage human activity in the region according to the principles of ecosystem-based management. The agreement also necessitates cross-border cooperation and can serve as a model for other regions that may benefit from inclusive research and management across national borders. The Arctic states, Arctic Indigenous peoples, and other stakeholders with an interest in promoting sustainability of the region should move forward with data gathering to promote co-production of knowledge and development of an inclusive and effective management plan with all possible speed.

STRATEGIC GOAL 9: ARCTIC TREATIES AND MARINE INFRASTRUCTURE

It can be argued that the most significant issue facing future Arctic Ocean use is the lack of marine infrastructure for providing emergency response, monitoring change, and facilitating safe navigation (including from enhanced bathymetry and hydrography). The only exceptions are modern infrastructure nodes in northwest Russia on the Kola Peninsula, in northern Norway, and on the coast of Iceland (Arctic Council, 2009). This Arctic marine infrastructure deficit hinders the full implementation and development of four recent Arctic treaties regarding search and rescue, oil spill preparedness and response, scientific cooperation, and the Central Arctic Ocean Fisheries Agreement. The lack of an Arctic state-driven investment strategy for marine infrastructure, even for an Arctic observing network that would monitor climate change, remains a major stumbling block to addressing this critical, large-scale challenge. Establishment of an observing network could also provide key, real-time observations to support safe and efficient Arctic marine operations, assist in the enforcement of the IMO Polar Code, and support the implementation of the four active Arctic treaties. Thus, this single and major infrastructure improvement would fill multiple, critical roles.

However, lack of commitment for shared funding and physical assets among maritime states, combined with diminished cooperation among the eight Arctic states and a pause within the Arctic Council, hinders near-term agreement on urgent needs. At the same time, the IMO Polar Code demands more attention be given to coastal infrastructure based on mandatory regulations designed to prevent the discharges of sewage and garbage; the practical issue is that few facilities exist around the Arctic Ocean to support the new, now binding rules and regulations. A longer-term strategic perspective is necessary. The role of public-private-partnerships must be fully explored where the maritime industry is a key investor and stakeholder in developing Arctic marine infrastructure. Potential areas of infrastructure cooperation between governments (national and regional) and private industry include: communications systems; ship traffic monitoring and surveillance; port development; regional response and recovery equipment; remote, coastal discharge facilities; commercial icebreaker support agreements; weather and sea ice information systems; marine salvage support; and future marine traffic routing systems. Marine industry experts must be full partners in all gap analyses that review Arctic preparedness and response operations conducted by the Arctic states, international and Indigenous organizations, and nongovernmental organizations.

STRATEGIC GOAL 10: ROLES OF THE MARINE INSURANCE INDUSTRY AND SHIP CLASSIFICATION SOCIETIES

The roles of the marine insurance industry and ship classification societies are vital to the continued implementation and long-term success of the IMO Polar Code. As a broad policy framework, the Code has provided both of these marine industries with a set of uniform, nondiscriminatory, and international rules and regulations. Both are key to evaluating the future risks of polar marine operations and to the creation of a truly uniform Arctic maritime governance regime, a goal identified in AMSA (Arctic Council, 2009). The ship classification societies individually and together in their representative body, the International Association of Classification Societies (IASC), have taken the lead to further develop the elements of the Polar Ship Certificate and the Polar Water Operational Manual; they are engaged in refining the Code's technical details, particularly construction standards, and further development of the seven Polar ship classes (PC1, the highest, to PC7, the lowest). The flag state maritime authorities and ship classification societies must continue to work closely together in establishing the certificate and the manual. The marine insurers and ship classification experts can also have key roles in the advancement of the Polar Code as a long-term framework for uniformity and harmonization of existing national Arctic shipping regimes. Finally, the marine insurance firms and classification societies are integral to the long-term enforcement of the Polar Code through their close relationships with the flag state maritime administrations and the marine operators.

STRATEGIC GOAL 11: ROLES OF THE INTERNATIONAL WHALING COMMISSION

The International Whaling Commission (IWC) has important roles to play in the protection of the Arctic marine

environment and in creating measures to reduce the risks to Arctic marine mammals. The IWC must also consider the challenges and complex issues of Arctic subsistence hunting and whaling. Mitigation measures for threats to marine mammals include noise reduction, speed restrictions (to reduce ship strikes), and marine traffic separation schemes or routes (IWC, 2014). The impacts of sound/noise on marine mammals have gained the attention of the IMO, which is reviewing the guidelines on the reduction of underwater noise. The IMO and IWC should develop close cooperation on addressing noise impacts in the ocean, perhaps in partnership with the Inuit Circumpolar Council (to gain Indigenous perspectives) as an IMO observer. Developing effective measures for mitigating the impacts of noise in all coastal waters and high seas, especially those of the Arctic Ocean, is extremely complex and requires the participation of many stakeholders and actors, including the Arctic states and their maritime agencies, the IWC, the IMO and other intergovernmental organizations, marine operators, subsistence communities and their representatives, ship classification societies, and nongovernmental organizations. Data collection and sharing, and assessment of threats, are key issues. Effective monitoring and compliance measures are equally essential for implementation and long-term enforcement. The IMO Correspondence Group that is currently reviewing the existing vessel noise reduction guidelines must consider ways to make the current guidance more effective, examine potential new technological and operational measures, and determine if there is a role for mandatory measures in additional to those that are voluntary.

STRATEGIC GOAL 12: COMMUNICATIONS AND ENHANCED ARCTIC WATERWAY INFORMATION

Improving the quality and relevance of information communicated to ships operating in the Arctic Ocean is a critical need. Achieving this will require having reliable communications systems that provide near-real-time and high-quality weather and sea ice information, including direct satellite imagery and environmental data as well as analyses sent as products by national weather and ice centers. Greatly improved regional and local communications between transiting ships and Arctic coastal communities are also required. Today's electronic chart displays and information systems, coupled with digital Global Positioning Systems (GPSs), have revolutionized ship navigation. Safe navigation in the Arctic Ocean has been greatly enhanced by precise, real-time positioning integrated with key environmental and navigation information.

The next step in improving information transmitted to ship pilothouses is development of an electronic "coast pilot" that includes detailed information that is perhaps unique to Arctic marine operations. Information to be provided in a pilothouse display would include areas of subsistence hunting (for whales, seals, walruses, fish, and birds) as provided by Indigenous surveys, voluntary ship routing measures, marine mammal seasonal migration patterns, electronic or virtual aids to navigation, high-resolution bathymetric (charting) information for coastal shallow-water operations, national and international boundaries, places of refuge for ships in distress or in need of assistance, and Arctic marine areas of heightened and ecological and cultural significance. This concept, developed by the Marine Exchange of Alaska, a public-private partnership, uses an advanced vessel-tracking system to enhance marine safety, protect the marine environment, and prevent maritime disasters (https://www.mxak.org/). Information on local subsistence hunting and whaling could be communicated electronically in near-real time. Testing a prototype electronic coast pilot for Arctic waters is feasible and could be funded by a public-private partnership (with marine operators), an Arctic state coast guard, or a maritime administration. Better and faster communication of critical maritime information between ship operators and other users of Arctic coastal waters is a marine safety imperative.

CONCLUDING COMMENTS AND RECOMMENDATIONS

Complexity and uncertainty will be constants in future Arctic marine operations and shipping. The only tangible certainty in the twenty-first century is continued warming at the top of the world and the resulting glacial melt and striking changes in sea ice thickness, extent, and character. Multi-year sea ice will disappear, perhaps before mid-century, and seasonal ice will be the norm throughout the Arctic Ocean. This continued retreat of sea ice will provide further marine access and likely stimulate increased traffic. However, new marine traffic will be constrained by the economics of the global shipping enterprise, Arctic natural resource developments (and their linkages to world commodity prices and markets), new technologies (such as new fuels for powering ships), and surely global geopolitics.

Despite many challenges, there are clear pathways ahead, and action can be taken on specific recommendations. Table 2 lists 10 equally important, high priority recommendations for advancing protection of the Arctic Ocean. Each can be considered a potentially notable, effective advance, and all are considered executable. The breadth of the recommendations highlights the complexity of the approaches and measures that can and should be taken to the protect Arctic residents and the marine environment.

Russia's invasion of Ukraine in February 2022 has caused many unforeseen and unintended consequences for the Arctic. The work of the Arctic Council has been paused, and scientific cooperation has been highly disrupted. The pace and overall economics of Arctic development, particularly in the Russian sector, have been severely affected, with sanctions, the termination of substantial international investments, and the disruption of components of global shipping. However, critical work on protecting the Arctic Ocean that *will* continue includes development of ongoing rules and regulations at the IMO on air emissions, use of heavy fuel oil, and the addition of smaller vessels under the IMO Polar Code. Beyond the purview and engagement of the Arctic Council, other international organizations with Arctic state delegations in the lead will take up the mantle of protecting the Arctic Ocean. The marine insurance industry and ship classification societies are advancing their work related to high-latitude marine operations and modern ship safety requirements. Further implementation of the four recent Arctic treaties will be more problematic in the short term, but long-term investments and cooperation (among the Arctic states, non-Arctic states, and industry) are plausible with a focus on the practical aspects of marine safety and environmental protection.

Protecting Arctic human populations and the marine environment remains a long-term, cooperative venture among the maritime states, Arctic Indigenous peoples, and the global maritime industry.

TABLE 2. Near-Term Action Items: Ten High-Priority Recommendations to Advance Protection of the Arctic Ocean

- Conduct a comprehensive review and gap analysis on the implementation and enforcement of the IMO Polar Code.
- Expand the IMO Polar Code to include fishing vessels.
- Designate an "Arctic Ocean Emissions Control Area" similar to other marine areas (Baltic Sea, North Sea, North America, and Caribbean Sea).
- Begin to immediately transition away from heavy fuel oil and significantly reduce black carbon emissions from Arctic shipping.
- Include Indigenous knowledge in all applicable Arctic research and observation networks.
- Initiate a permanent participant-led circumpolar survey of Indigenous Arctic marine use.
- Form a working group led by IMO, IWC, and ICC on the impacts of underwater noise/sound on Arctic marine mammals.
- Commence preliminary work and negotiations on an Arctic state "Arctic Port State Control Agreement."
- Conduct a study on the potential roles of public-private partnerships in closing the Arctic marine infrastructure deficit.
- Conduct a feasibility study of an electronic coast pilot for an Arctic waterway (such as Bering Strait).

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PERSPECTIVE

FUTURE ARCTIC MARINE NAVIGATION
COMPLEXITY AND UNCERTAINTIES

By Lawson W. Brigham

Many uncertainties and a complex suite of drivers of change are influencing the future of Arctic marine operations and commercial shipping. Most notably, the well-documented reduction of Arctic sea ice extent and thickness and the transition from thick, multi-year to seasonal, first-year ice are profound responses to anthropogenic climate change. The Arctic Ocean is becoming more navigable, with greater marine access now attained in most regions. The possibilities for longer seasons of marine navigation during spring, summer, and autumn are real, but the vision of new, year-round (routine) Arctic shipping that could alter global trade routes remains highly implausible. Arctic shipping remains largely destinational, with ships traveling into the Arctic Ocean to conduct an economic activity (Lasserre, 2019).

Significant progress has been made during the past decade as researchers have analyzed the output of advanced Arctic sea ice simulations (from global climate models) and then quantified what the projected ice covers mean for marine access and longer navigation seasons. In addition, as marine areas become partially ice-covered for longer periods of time, a practical ship navigation issue has emerged: a more mobile and dynamic ice cover will likely create unforeseen challenges (e.g., more frequent ice ridging) to safe, efficient, and more economically viable ship transits.

A key strategy for evaluating the future of Arctic marine use is to take a more holistic and high-level view of the many factors, or drivers of change, beyond the profound changes in Arctic sea ice that will determine the plausibility of future destinational and trans-Arctic voyages. Three influential drivers are critical to better understanding this future: (1) the economic viability and pace of Arctic natural resource developments and their connections to global commodity pricing and markets; (2) the complex economics and the array of stakeholders within the global shipping enterprise—including ship owners, flag states, ship classification societies, and the marine insurance industry; "just-in-time" container cargoes or bulk commodity cargoes that can be stockpiled and shipped seasonally; shipbuilding and advanced technologies; available marine infrastructure to support trade and operations along shipping routes; and other economic challenges such as long-term ship financing unique to global shipping; and (3) international governance and Arctic national regulations for ship operations throughout the Arctic Ocean—including the United Nations Convention on the Law of the Sea, UNCLOS, as the legal framework for the Arctic Ocean; the International Maritime Organization's mandatory rules and regulations for ships operating in polar waters (the IMO Polar Code); and special regulations for ships operating along Russia's Northern Sea Route and within the waters of the Canadian Arctic (Brigham, 2021). The current and unforeseen war in Ukraine should be considered a wildcard and a highly disruptive geopolitical event that has changed the calculus for Arctic state cooperation and future economic development in the region.

The plausible future scenarios presented in the Arctic Council's *Arctic Marine Shipping Assessment* (AMSA) released in April 2009 revealed the complexity and challenges of fully understanding the future of Arctic marine navigation. The process of creating the AMSA scenarios identified a suite of uncertainties or influential drivers of change bounded by two major factors that formed the axes in a four-scenarios matrix: resources and trade (the level of demand for Arctic natural resources and trade) and governance (the degree of relative stability of rules for marine use both within the Arctic and internationally). The four AMSA scenarios, a set of stories developed around carefully written plots using many of the more than 120 uncertainties uncovered in AMSA's strategic discussions, include *Arctic Race*, *Arctic Saga*, *Polar Lows*, and *Polar Preserve* (Arctic Council, 2009; **Figure 1**).

Importantly, the AMSA scenarios workshops revealed a host of uncertainties that included influential and broad drivers such as a stable legal climate or framework, global oil prices, new Arctic resource discoveries, limited or seasonal windows of Arctic marine operations that impact the economic viability of Arctic shipping, a major Arctic shipping disaster, rapid climate change and climate change becoming more disruptive sooner, the safety of other global trade routes, Arctic route transit fees, new global agreements on polar ship construction rules and standards, the escalation of Arctic maritime disputes, conflicts between Indigenous and commercial use in Arctic waters, Arctic maritime enforcement efforts, and the entry of new maritime nations (China, Japan, and South Korea) to Arctic

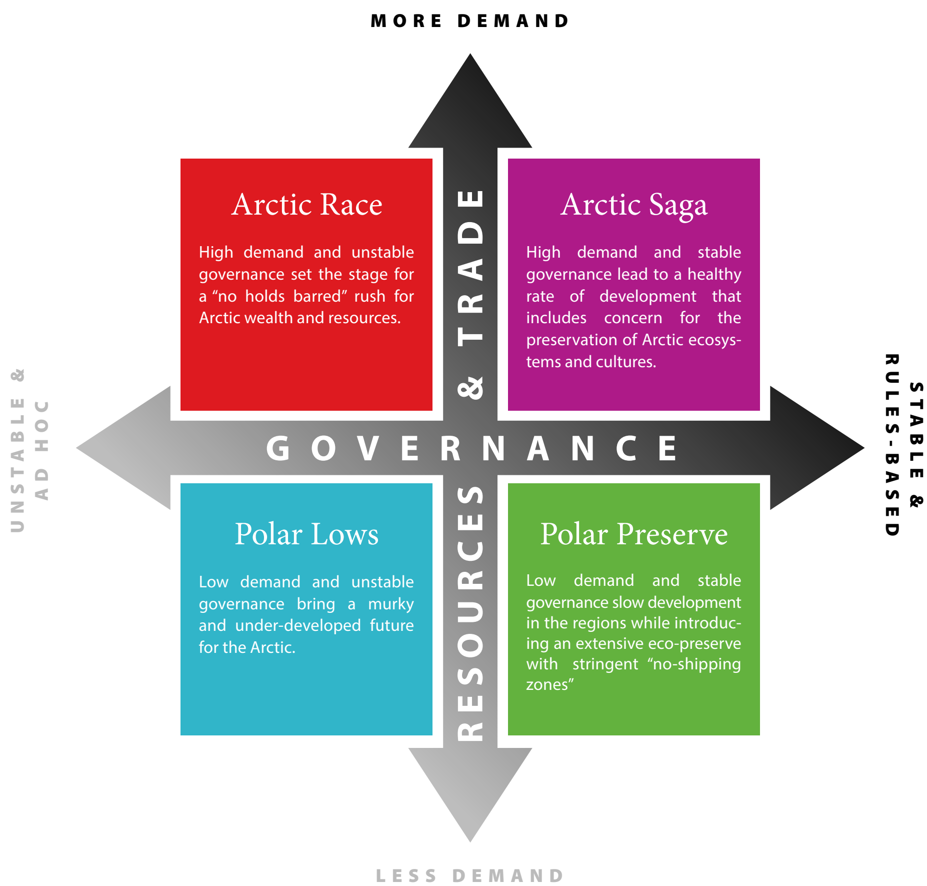

FIGURE 1. Arctic marine navigtaion scenarios matrix with the two framework drivers or uncertainties. *From Arctic Council (2009)*

shipping (Arctic Council, 2009). There is little doubt the most valuable outcome of the AMSA scenarios work was to identify the great complexity and inherent range of global factors that can influence the future of Arctic marine operations and shipping.

Future research regarding Arctic marine navigation must address this fundamental issue of complexity and focus on interdisciplinary approaches. A full range of influential factors, many global and foremost among them economic drivers (as well as climate change, governance, social impact, geopolitics, and many others), need to be integrated with any research strategy and framework. Examples of key questions and potential research topics include:

- Given that sea ice thickness is one of the most important factors in ice navigation, how can new ice thickness observations and sea ice maps assembled from satellite observations, coupled with Polar Class ship capabilities, be used to determine Arctic marine access and assess longer seasons of navigation?
- How will the IMO Polar Code impact the overall economics and operations of future Arctic commercial ships?
- What is the potential for public-private partnerships (between public institutions and the global maritime industry) to invest in Arctic marine infrastructure that supports regional economic development, improves marine safety, and enhances environmental protection?
- How has the war in Ukraine impacted Arctic economic development, international cooperation in Arctic maritime affairs, and future Arctic marine transportation systems?
- What scenarios for bulk shipping in the Arctic Ocean—along the Northeast Passage, the Northwest Passage, and routes across the Central Arctic Ocean—can be developed to identify economically viable seasons of navigation in future decades?
- What are the near-term and long-term futures of shipping coal, oil, and liquefied natural gas out of the Arctic to global markets?

Despite the extraordinary retreat of sea ice and the increase in Arctic Ocean marine access, the future of marine operations at the top of the world remains highly uncertain. A complex mix of factors, including key economic drivers, and the feasibility of Arctic cooperation will determine the future viability of Arctic ship navigation.

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INCREASED PREVALENCE OF OPEN WATER DURING WINTER IN THE BERING SEA

CULTURAL CONSEQUENCES IN UNALAKLEET, ALASKA, 2022

By Kaare Ray Sikuaq Erickson and Tero Mustonen

Spring along the Unalakleet coast, 2022.
Photo credit: Ikaaġun Engagement

ABSTRACT. Widely recognized environmental changes have been negatively impacting communities in the Arctic for decades. The increased prevalence of open water in the Bering Sea during winter months, also known as sea ice loss, has uprooted annual traditional subsistence activities across the Bering Sea region. This article investigates the consequences of sea ice loss on traditional subsistence activities in Unalakleet, Alaska. In conjunction with the loss of sea ice over the past 30 years, the winter season in Unalakleet has shifted from cold and dry weather regimes to warmer and wetter winters. The change in winter weather and the increased prevalence of open water in winter has deeply impacted the people of Unalakleet by affecting environmental conditions and the availability of subsistence of resources, notably influencing winter and spring marine mammals hunts that people in the Unalakleet area have relied on for thousands of years. This article is guided by the perspectives, knowledge, and intuition of people from Unalakleet, and looks specifically at how the increased prevalence of open water in the Bering Sea during wintertime has impacted traditional subsistence rounds (the succession of food resources through the seasons) in Unalakleet, Alaska, in 2022.

INTRODUCTION

Environmental changes have been negatively impacting communities in the Arctic for decades. Major shifts in weather patterns and seasonal conditions have been widely recognized and made known by Arctic locals and researchers. Some of the more generalizable changes that affect communities across the Arctic include thawing permafrost, more frequent storm activity, increasingly warm and wet winters, and loss of sea ice. On the local level, each individual community in the Arctic is unique: the geographical characteristics of these communities vary from sandy coastal bluffs to solid bedrock, culture and history are specific to the local areas, every Arctic community faces its own unique sets of challenges and crises, and each community deals with the challenges it faces in its own way.

This article focuses on one Bering Sea community, Unalakleet, at the mouth of the Unalakleet River on the eastern Norton Sound coast (Figure 1). People in Unalakleet have recognized major changes in environmental conditions that have grown increasingly worse over the past 30 years (F. Doty, 2022; G. Doty, 2022; Ivanoff, 2022; Katchatag, 2022; Katongan, 2022; Mustonen and Van Dam, 2021; Paniptchuk, 2022; Slats et al., 2019; Towarak, 2022). One of the major changes people are facing in Unalakleet is the loss of cold and continuously frozen winter seasons. This is related to the loss of sea ice, which leaves a majority of the Bering Sea ice-free during winter months, including the waters adjacent to the Unalakleet area. The open water causes warmer and wetter (e.g., rain on snow events) episodes in winter. The central question we seek to answer here is: how has the loss of seasonal sea ice, and thus open water in winter, impacted traditional subsistence life in Unalakleet, Alaska? This article relies

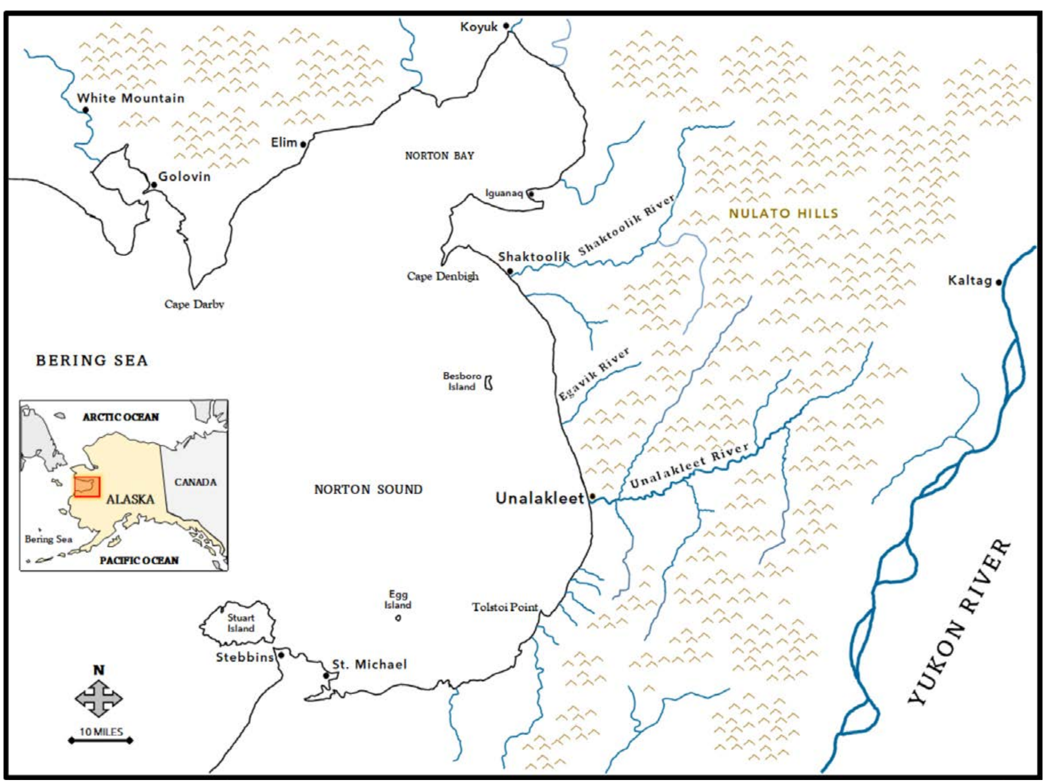

FIGURE 1. Map of the Norton Sound area in western Alaska. *Illustration by Ikaaġun Engagement*

on the observations, experiences, and intuition of people who live in Unalakleet. A variety of resources are utilized, including publications by Unalakleet people, materials directly based on their perspectives, the life experiences of the authors, and unpublished interviews between the authors and Elders (and providers) of Unalakleet. Additional scientific publications and data are referenced to provide context and to further reinforce local observations. Many of the quotations cited in this article are derived from a series of interviews that took place in 2022 in Unalakleet for a project focused on ecological change and Indigenous observing, planned in association with the Native Village of Unalakleet (NVU) and supported by the European Union-funded Pan-Arctic observing System of Systems: Implementing Observations for societal-Needs (Arctic PASSION).

INDIGENOUS PERSPECTIVES

This paper may be considered as presenting an Indigenous perspective, as the first author identifies as an Alaskan Indigenous person (Inupiaq and Scandinavian descent). He was raised in Unalakleet and the surrounding area as a hunter and fisherman—and still frequently travels in and around the greater Norton Sound area for subsistence activities and for long distance wintertime snowmachine (snowmobile) trips. The article can also be considered as being based on Indigenous perspectives because it relies on and directly quotes many Unalakleet Indigenous people.

Human perspectives vary drastically among individuals and within ethnicities, cultures, and families. Other than the direct quotes and other references cited in this article, all other text represents the authors' viewpoints and perspectives. The authors hope this text uplifts the Indigenous voices of Unalakleet. It is also meant to provide readers one example of how, when considered at a local level, people in the Arctic are navigating extremely daunting issues, such as the uprooting of traditional subsistence rounds (the succession of food resources through the seasons), and attempting to overcome these challenges in order to ensure healthy futures.

CONTEXT/SETTING: UNALAKLEET

The community of Unalakleet is located on the eastern Norton Sound coast of the Bering Sea at the mouth of the Unalakleet River (Figure 1). The village is the only community in the Unalakleet River basin, which includes 3,246 miles (5,334 km) of river and streams spread over 2,082 square miles (5,392 square kilometers) (BLM, 2000). Headwaters of the main river originate in the Nulato Hills, which average between 1,000 and 2,000 feet (0.3 and 0.6 km) altitude and extend on both the northern and southern sides of the river valley. The foothills nearest to Unalakleet are composed of long ridges and slopes that run from southwest to northeast and meet the coast just north of the village (see coastal cliffs in Figure 3).

Unalakleet is not accessible by road—only by air or seasonal barge. Subsistence resources, most notably salmon, marine mammals, moose, caribou, waterfowl, and berries, make up a majority of most locals' diets. As in all rural areas of the Arctic, fuel and groceries are very expensive in Unalakleet due to the limited access. In addition to the natural resources available to them, people in Unalakleet access "store-bought" resources purchased from the local grocery stores or flown in from hub locations in Anchorage, Fairbanks, or Nome, and regular postal service, also relatively expensive, allows them to order items from online retailers.

Unalakleet has a deep and rich cultural history. The optimal location of the village provides fresh and clean water sources, good gravel sites for building, and access to a plethora of land and sea resources, such as fish, birds, land animals, berries, plants, and increasingly variable populations of salmon and marine mammals. Historically, Unalakleet has been known as a strategic location for trade among several cultural groups because of its proximity to both the Bering Strait area and the interior Yukon, with trail access through the Unalakleet-Kaltag portage. The portage is a historic trading route now included as part of the famous Iditarod Trail. People from Unalakleet traditionally harvested extra marine resources, including sea mammal products such as seal oil and oogruk (bearded seal) skins to trade with interior communities for furs, wooden spoons, and other products (Koutsky, 1982).

Archaeological evidence suggests the eastern Norton Sound has been occupied continuously for at least 3,000 years (Giddings, 1960; Dumond, 1978), with the specific location of Unalakleet being occupied for at least 2,000 years (Lutz, 1973). Ticasuk, a respected educator, historian, and author from Unalakleet remembered her Elders repeatedly telling her stories about generations of ancestors of the local people in Unalakleet. The ancestors lived at *Ayaatayat*, "the original village at Cape Denbigh," which Ticasuk said "is the grandfather of all Eskimo villages in the area," organized roughly 10,000 years ago (E. Ivanoff Brown, 1987).

In the following sections, we present oral histories and Indigenous knowledge of the weather and subsistence rounds from Unalakleet. We wish to integrate these materials with the knowledge gained by the scientific community.

It is well established in the scientific literature that greenhouse gas emissions from the industrialized world and land use changes are causing far-reaching and accelerating change to the climate and ecosystems of the circumpolar North. Temperature increases across Alaska vary greatly by season and location, with larges increases occurring in fall and winter in the western and northern regions of the state.

Figure 2 plots the trend in annual average surface air temperature at Unalakleet for the available record (1950 to 2020), showing an approximately 5°F (2.8°C) increase in the annual average surface air temperature since 1950.

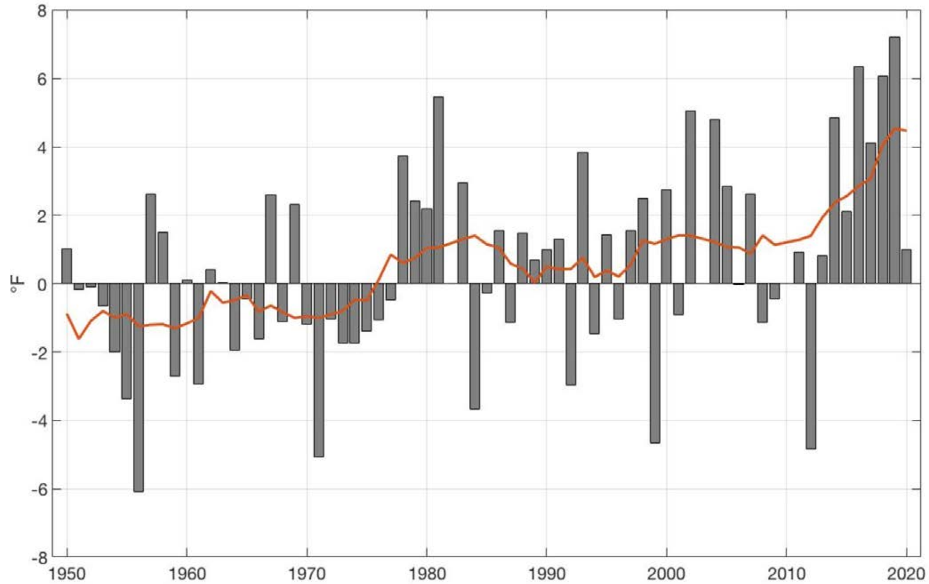

FIGURE 2. Annual average surface air temperature trends (gray bars, overall average traced in red) at Unalakleet, Alaska, 1950–2020, calculated relative to a base period of 1961–1990. There has been an approximately 5°F (2.8°C) change in the annual average surface air temperature since 1950, based on a least-squares linear fit. Data from the NOAA National Centers for Environmental Information (NCEI) Integrated Surface Database (ISD) data set. *Graph created by Snowchange Cooperative, 2022*

HISTORICAL WEATHER PATTERNS IN UNALAKLEET

Before climate-driven impacts began making large changes to local subsistence cycles (roughly over the past 30 years), the annual weather cycle in the Unalakleet area would shift between two major seasons: cold and dry winters followed by cool and wet summers. Fall, or the transition between summer and winter, was characterized by short stormy periods that ended when Norton Sound and the northern Bering Sea froze solid. Springtime, or the shift between winter and summer, was characterized by relatively calm periods of weather during the "breakup" or thawing of ice and snow. In 1985, the City of Unalakleet produced a village planning document that described the climate and weather the citizens knew to expect every year:

Although Unalakleet's climate is classified as transitional, two distinct seasons can be distinguished: a dry, cold winter typical of inland continental regimes; and a cool, wet summer, typical of maritime climates. Seasonal change correlates closely with changes in sea ice conditions. Norton Sound is ice-covered in winter, and ice-free in the summer. (City of Unalakleet, 1985)

As noted by the City of Unalakleet, the two major seasons—the cold, dry winters, and the cool, wet summers—correlated directly with the presence or lack of sea ice. The entire Norton Sound would typically freeze over for the winter months, as Elder Millie Katongan remembered: "When I was growing up, the ocean used to have ice as far as you can see. Take long time, even after Memorial Day [May 29], there would still be ice floating around" (Katongan, 2022). Another Unalakleet Elder, Sheldon Katchatag Jr., remembered a roadhouse located on Besboro Island (*Kikiktaq*) used as a resting place by dog-sled mail carriers as they traveled the over-ice trails that cut straight across the frozen Norton Sound during the winter months:

An example is the roadhouse at Kikiktaq, Besboro Island. They needed that lodge there for their dog mushers that were carrying the mail. And they used to run almost straight from here [Unalakleet] to Cape Denbigh, to Elim, they could go straight [across the ice] because the water froze that much. (Katchatag, 2022)

TRADITIONAL SPRINGTIME HUNTING

One of the most important times of the year, traditionally, was oogruk and seal hunting. Local people in Unalakleet distinguish the much larger "oogruk" separately from all other seal species, which are referred to as "seals." Oogruk and seal hunting was in the springtime, "when the ocean ice is floating around in chunks. During this time of year, the seals rest on the ice after migrating from the south" (Creative Writing Class of CHS, 1978). As Jorgensen (1984) stated, "the activities of the late spring season consumed the attention and energies of the village. Every chance they got people went out looking for oogruk." Hunting for marine mammals was one of the most important activities for Unalakleet people, as local Inupiaq educator Martina Bailey (Partnow, 1986) shared in 1986:

But of all the animals we hunted, the seal was the most important. The best times to hunt seals are spring and fall. The seals are migrating at those times, and many are in Norton Sound, the part of the sea that is next to Unalakleet. Seals will bask on ice floes.

The late Unalakleet Elder, John Auliye, explained in 1978, "Long ago old hunters used to pull their kayaks way out to an open lead on the ice and hunt seals. Nowadays they use snowmachine" (Creative Writing Class of CHS, 1978). The edge of the ice would typically be so far offshore that hunters traditionally used Egg Island (34 miles [55 km] from Unalakleet) for a basecamp from which to pull their kayaks with a sled over the "old ice" (thick, shore fast ice) to the ice leads further from Egg Island (E.T. Ivanoff Brown, 1974).

The traditional seasonal subsistence rounds in Unalakleet correlated directly with ocean conditions, particularly during spring. A federal report on subsistence activities from the early 1980s by Jorgensen (1984) found that in Unalakleet, "Ice conditions and water temperatures affect the time and arrival of the spring birds, fish, and sea mammals, whether they come within hunting range, and their numbers." Emily Ticasuk Brown (Ivanoff) described the change of weather in the spring, "During the latter part of May on the coast of the Norton Sound, the Eskimos are usually set free from the firm grip of the wintry blast" (E.T. Ivanoff Brown, 1974). Springtime has always been an extra special time for communities in the Arctic with the return and reciprocity of animals and plants. Unalakleet Elder Lorena Paniptchuk fondly remembers the excitement for fresh foods from spring hunts:

Men go with dog team, when they go hunt caribou, we're real happy. If they get, they'll share, each home, enough to cook even. When they go seal hunting, when they come home, they bring and cut enough for a pot for each home. Boy, we used to be real happy, I can't wait for them, like April, that's the time they get crab and those rockfish when the ice first go. That's why I still like to go rock fishing, I just got to have them springtime. (Paniptchuk, 2022)

PREDICTABLE SEASONAL SUBSISTENCE ROUNDS

To survive in the Arctic, people must constantly overcome challenges, obstacles, and crises. Over a very long time, Indigenous peoples in the Arctic have built a body of knowledge and technology to efficiently utilize environmental and subsistence resources that follow seasonal shifts in climate and weather conditions. Predictable seasonal rounds were a common characteristic across all communities in the Bering Sea region. In 1982, while describing more general characteristics that all Bering Sea communities share, Fitzhugh and Kaplan (1982) spoke of the distinct and predictable seasonal rounds that allowed local residents to "make efficient use of game available at different places and times of the year. For the most part, these changes are broadly predictable from one year to the next" (Fitzhugh and Kaplan, 1982).

Traditionally, Unalakleet people were able to maintain a schedule that followed an annual cycle. During the early 1980s, a group of researchers worked closely with local leaders and stayed in Unalakleet for six months from late winter until the following fall. According to Jorgensen (1984), the researchers took part in subsistence activities to document ethnographic information about "the manner in which they (Unalakleet residents) use their environment, the ways in which they are organized to do so, and the meanings which they attribute to it." The detailed 400-page report frequently refers to the seasonal subsistence cycles in Unalakleet:

In their mental calendar, people know the order and pace with which resources follow each other, as well as the combination of resources that are available at any given time. People fine-tune their mental calendar each year, figuring for that year as precisely as they can for days or weeks the arrival of the foods, their duration and time of best harvesting, and the speed at which they will follow each other. (Jorgensen, 1984)

People in Unalakleet would be able to go about their seasonal rounds by carefully watching and responding to the environment:

People draw on their own knowledge of the cycle and habits of the animals and plants, of the influence of the weather and ice conditions on the availability of these resources, and the signs they observe in nature which tell them more exactly what the year's calendar will be. (Jorgensen, 1984)

Of course, people in Unalakleet still live, day-to-day, directly in response to weather, climate, and the availability of resources. Unalakleet Elders reminisce about the traditional or normal, seasonal schedule they remember as children and young adults:

So, when I talk about the old subsistence lifestyle (in Unalakleet), everything was on schedule, you know, because life was pretty much normal, the way they knew it. (Towarak, 2022)

CONSEQUENCES OF SEA ICE LOSS TODAY

Disruptions to Traditional Subsistence Cycles

Climate-driven impacts are some of the biggest threats to traditional subsistence cycles in Unalakleet. As quoted in the NOAA Arctic Report Card 2019, Unalakleet Elder Jerry Ivanoff acknowledged that, "There's less and less snow, and there's less and less ice, and that means trouble, not only (for) us hunting and fishing, but the animals that we depend on" (Slats et al., 2019). Today, people in Unalakleet are faced with completely unpredictable seasonal rounds. Unalakleet Elder, Clarence Towarak Jr., or "Junie," shared that people need to continually adjust to unpredictable conditions:

It's puzzling for us, anyway, because we're all used to a certain day, the salmon are supposed to be here, certain season they're supposed to be running good. Certain season they're all done. But it's changing so much, you have to figure out what's happening, and do things accordingly. (Towarak, 2022)

Marine Mammals Hunts

As noted, traditionally, the marine mammal hunt in the spring season was very important, and it is still extremely important to people in Unalakleet. However, after decades of increasingly variable conditions, hunters in Unalakleet struggle to provide their families and fellow community members with oogruk and other marine mammals. One of the primary issues is that oogruk need flat ice to rest and live on, and for most of the year, the ice simply does not exist in the Bering Sea (**Figure 3**). One hunter in Unalakleet shared that:

Now days you can go boating in December, January. Back then, you weren't able to go boating, it was all pure ice. You were able to go 15–20 miles out [on the ice]. Nowadays we don't have sea ice anymore. (G. Doty, 2022)

Even if you travel far out in the open water with a small boat and come across an oogruk in the water, if you are successful, it can be very dangerous to attempt to butcher the animal without a solid ice platform to work from, especially because many oogruk are too big to pull into smaller watercraft.

FIGURE 3. Norton Sound coast three miles north of Unalakleet showing open water and slush ice during spring 2022. Traditionally, shore fast ice would extend from the coast during this season *Photo credit: Ikaaġun Engagement*

Without that sea ice, you have to travel 15–20 miles [over open water] to just to get out where the oogruk are. And when you do catch it, usually you butcher it on a piece of sea ice, but without no sea ice, you would have to haul it 20 miles back to land or to a piece of sea ice to butcher it. (G. Doty, 2022)

Unalakleet Elder Jerry Ivanoff describes a hunting trip for oogruk in the spring of 2020 that forced him and his crew to travel over 200 miles (322 km) in open water to finally locate and catch one oogruk:

I normally go oogruk hunting right out here, right off our shore, I get them five miles out. Two years ago, I went oogruk hunting with my partners, Ronnie, Wayne, and Don. We went oogruk hunting, we went to Besboro Island, we went to Cape Denbigh, we went halfway to Koyuk, and we ended up at Iguanaq, you know on the ice out there. There's no oogruk, but there's seals all over [the shore-fast ice]. I'm looking for oogruk, you know, this is what I want to put on the table, something I've done my whole life. So, we come back down, go to Cape Denbigh, and we go out 20 miles, thinking we'd find ice. But there was no ice, so we V-lined it home. We filled up with gas, the next day we took off and ended up at Egg Island. There's no ice, just shore-fast ice with seals on it, and we can't get on it, because the weather is north wind. So we ended up spending the night at Egg Island, pretty cold. And then we took off in the morning, as soon as it got bright, we go to Stuart Island. And then from Stuart Island, the floating ice was 10–15 miles to the southwest, and we got an oogruk then. (Ivanoff, 2022)

Another Elder in Unalakleet reemphasized the struggles the oogruk hunters of Unalakleet face with the changes:

Things are changing so fast with this climate change, even the hunting is really hard, you can tell just by watching how these guys are struggling to get some oogruk. There aren't that many people that got oogruk this year [2022]. And the weather has been so bad, and it's all because of climate change. We're getting more and more storms that are not natural, at certain times of the year. (Towarak, 2022)

It is important to recognize that there are times every year that sea ice begins to form in the waters of Norton Sound surrounding Unalakleet. However, frequent storms and high wintertime winds tend to break up the ice and blow it away. Unalakleet Elder Sheldon Katchatag Jr., also known as "Shacky," explained the situation:

One of the things that concerns me the most is the loss of our winter ice. I was amazed that even though we had the sixth coldest winter on record this last 2021/2022, I assumed that we would have ice until May or June. Because we were having approximately 30 below weather in Nome just about every day. And I knew that ice was getting thick out there, and it was all covered. And I thought, as thick and as expansive as the ice is, I don't have to worry about Norton Sound not having ice next spring when I go hunting. And boy was I fooled. We had a December storm, when it finally warmed up, and we had two days of sustained winds in excess of 50 miles per hour, with peak gusts in the 70s, hurricane-force winds. And it blew for three days from the east, calmed down for half a day, and blew 60 miles an hour from the west for three days. And it blew me away. And it also blew the ice away. It never used to happen like that, whenever you had a really cold winter, the ice was there for the winter, and it would stay. (Katchatag, 2022)

Other Subsistence Activities

Although this text has focused largely on the spring marine mammal hunt, the loss of sea ice has negative impacts on several other subsistence activities. When sea ice is present in Norton Sound, it is used as a platform to travel up and down the coast to go caribou hunting, to hunt and trap fur-bearing animals (e.g., wolf, wolverine; Figure 4), and to set crab pots through the ice for wintertime crabbing. Caribou migrations can vary greatly in location from year to year. Over time, migrations can shift into and out of the Unalakleet River basin area. For several years, especially more recently, caribou have stayed far away from Unalakleet, requiring local hunters to travel extraordinarily long distances to catch caribou. One Unalakleet hunter explained the situation:

Our winter, we used to catch caribou right in our back yard, and now with the climate warming, we have to travel at least 200–300 miles [one way] just to catch our caribou during the winter season. Also, during the winters we used to do a lot of crabbing though the ice, and without ice during the winter we can't actually go and catch our subsistence crab. And it has an impact on us, because that's our traditional food that we eat during the winter is caribou and crab. And with climate warming, it's hard to travel without no snow, and there's tundra. (G. Doty, 2022)

In 2003, Palmer Sagoonik, a respected hunter, fisherman, reindeer herder, and leader in Shaktoolik, the next community 35 miles [56 km] up the coast from Unalakleet, talked about changes he already observed by the early 2000s in relation to the caribou migration, which was shifting more northerly. His perspective is crucial because reindeer herders tend to spend extensive time throughout the entire yearly cycle traveling the land and watching the conditions.

I think the caribou migration changed because of the weather pattern change. It's warmer up here and they can range further then they did back when it was colder. Weather had a lot to do with it. Freeze-up was later, spring was earlier… The winter seasons are not as cold. Back in the easy days, reindeer herding was easy because we didn't have as many warm spells, and we had a lot more snowfall. (Sagoonik, 2003)

FIGURE 4. A rare piece of ice allowed spring hunting in Norton Sound in 2017. *Photo credit: Frank Doty*

With increased moisture in the air from the open water, in addition to the warmer weather, the Unalakleet area now has a high number of rain events during wintertime. Rain in the winter can be devastating for the animals. They may have trouble accessing their food because winter rain forms a layer of ice that covers and encases the plants and foods. Reindeer and caribou are especially affected because the mosses they prefer become covered in ice, explains Unalakleet Elder Shacky:

So, because of the freezing rain events, it seals the food away from the caribou, they can't get at it. So, they didn't come down this year, and this is the first time I ever heard of people from Koyuk having to go like a hundred miles [north northeast from Koyuk] just to find caribou…and that's what worries me about winter storms where we get a lot of freezing rain. And this last winter was terrible as far as freezing rain, this place was dangerously slick. (Katchatag, 2022)

Icy conditions on the tundra due to moisture in the environment can also heavily impact the ability of hunters and overland travelers to cross the land during the winter, as explained by a Unalakleet hunter:

The winter is shortening. Back when I was a kid everything froze over in the middle of September when school started. But as you know now, it's rained every month throughout the winter… Traveling was tough this year [2021–2022], just having all ice [covering the landscape]. Traveling was limited this winter because if there wasn't any snow to cool off the [snow machine] engines, some people blew up their engines. (F. Doty, 2022)

Increased Coastal Erosion

We have focused here on how sea ice loss impacts traditional subsistence cycles, but it is important to note that the warmer winters and increased storms associated with open water in the Bering Sea during winter also significantly impact the coastal landscape. Although permafrost thaw is affecting both coastal regions and lands in the interior Arctic, lands adjacent to the coast surrounding Unalakleet have begun to thaw at extremely high rates, creating dozens of large sinkholes, some as big as a half-mile (0.8 km) wide, on the coastal banks near Unalakleet (**Figure 5**).

They [sinkholes] have really expanded in the last four years. I've watched the coast between here [Unalakleet] and Tolstoi Point. Just about every year another pocket of permafrost would thaw, and it would melt and dissolve all the mud around it, and it would melt so fast that it would just flow all the way to the beach. And at first there was only like three or four, mostly down on the hills…but they're on all the banks. (Katchatag, 2022)

FIGURE 5. Thawing permafrost resulted in a large, older sinkhole (left, with vegetation growth inside) and a new sinkhole (right, with dark soil) on the coast six miles from Unalakleet. *Photo credit: Ikaaġun Engagement*

CONCLUSIONS AND MOVING FORWARD

Changes in climate and weather are not only severely affecting Indigenous subsistence rounds in Arctic regions, they are profoundly impacting people across the globe, as the Secretary General of the United Nations stated:

Our climate is heating rapidly. Floods, droughts, heatwaves, extreme storms, and wildfires are going from bad to worst with ever-alarming frequency. Heatwaves in Europe, colossal floods in Pakistan, prolonged and severe droughts in China, the Horn of Africa, and the United States. There is nothing natural about the new scale of these disasters. (United Nations Web TV, 2022)

Communities across the Arctic face unique sets of challenges. The impacts of major climate changes, such as thawing permafrost, warmer and wetter winters, and loss of sea ice, are felt by many communities and regions across the Arctic. The impacts of the loss of sea ice in the Bering Sea, and the correlated increased prevalence of open water during winter and spring months, have uprooted traditional subsistence rounds in communities across the Bering Sea coasts. During a presentation in 2019 at the National Academy of Sciences in Washington, DC, Delbert Pungowiyi, a respected leader from the Bering Sea region, described how sea ice loss has impacted his home community of Savoonga:

When there is open water, it is not winter to us. Only when the whole of the Bering Sea is completely locked up, that is winter. The winter we have now is three months, to us that is not winter anymore. (Pungowiyi, 2019)

Over the course of the last 30 years, the increased prevalence of open water during winter months has severely impacted the traditional subsistence rounds in Unalakleet. Historically, the waters near Unalakleet would be frozen solid throughout the winter, which would cause cold and dry winters, similar to interior Alaska winter climate regimes. With the increased prevalence of open water in the Bering Sea, the adjacent coastal areas have warmer and wetter winters, which cause a suite of issues associated with subsistence hunting and gathering. The lack of sea ice does not allow Unalakleet residents to regularly access and harvest marine mammals upon which they have traditionally relied. Good hunting conditions are rare, and the changing marine landscape has forced marine mammals and other species to change migration patterns, further complicating subsistence hunts.

As noted in this paper, the loss of sea ice and associated open water in the Bering Sea is just one of the major issues facing the people of Unalakleet. The most notable "other" issue is the decline in annual salmon returns and the decreasing sizes of salmon. It is important to avoid assuming general climate changes are the only factors responsible for the decline in annual salmon returns and salmon size. Indeed, many people in Unalakleet and across Alaska feel that certain commercial fishing activities are impacting the subsistence salmon harvest and that changes in the environment are being used as an excuse.

It is the nature of Arctic people to overcome extreme challenges and to effectively move on to the next obstacle.

Indigenous and local people in the Arctic have continued to adjust their subsistence cycles in response to major changes to weather and seasonal patterns and shifting migration of animals. People in Unalakleet miss the old days, not just for nostalgia, but because the climate was much different, much more predictable, and most important, much more reliable. They miss the cold and dry winters that allowed them relatively easy travel to access resources.

It sure has changed in 20 years, from what we're used to having, and having that taken away. And having to adjust to it, adjust to the land, because you can't change it. (G. Doty, 2022)

An important characteristic of many people in Unalakleet—and maybe the central key to survival in the Arctic—is to have a positive outlook in the face of challenges and crises.

Things have changed. I almost feel like I need to move a little farther north, just to be in the Arctic [laughter] just cause it's so warm. I mean, no winters, and monsoon season all summer long. (F. Doty, 2022)

The people of Unalakleet, like those in every community in the Arctic, will continue to face and overcome challenges as they arise. The question is: are any of these challenges avoidable? Threats to the subsistence lifestyle in rural areas of the Arctic, whether from environmental changes or over-utilization of commercial resources, are extremely daunting to local and Indigenous communities. However, Arctic communities are made up of intelligent, thoughtful, and strong people who have children, futures, and unique traditional lifestyles that will continue. Our people will hold onto memories, prepare for the worst, fight for the best, and continue to live.

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SIDEBAR > CO-PRODUCTION OF KNOWLEDGE IN ARCTIC RESEARCH

RECONSIDERING AND REORIENTING AMIDST THE NAVIGATING THE NEW ARCTIC INITIATIVE

By Matthew L. Druckenmiller

In 2016, the National Science Foundation (NSF) identified 10 "Big Ideas" for advancing science and engineering research and guiding long-term US research investments. Navigating the New Arctic (NNA) was one of those big ideas, highlighting NSF's continued commitment to funding research to help societies respond to a warming Arctic. NNA focuses on *convergence*—collaborations formed from deep integration across disciplines and knowledge systems to address vexing and complex research challenges that are pivotal for meeting societal needs (Wilson, 2019). The NNA initiative has funded over 100 individual and collaborative research projects since 2017, addressing topics ranging from thawing permafrost, to shifting weather patterns, increasing shipping, and adapting food systems. Research teams funded by NNA to work across the Arctic are composed of scientists from diverse disciplines, Indigenous knowledge holders, practitioners, planners, and engineers.

Many NNA projects also emphasize *co-production of knowledge*—a collaborative and inclusive process that brings together Indigenous knowledge and science in a holistic view to generate new understandings for addressing research, policy, and management interests (Yua et al., 2022). Co-production of knowledge is not new; it has had a long history in Arctic research. However, today there is heightened attention to the systematic changes needed to make the process equitable across all stages of research, from initial conceptualization and design to the sharing and application of the information and knowledge that is generated.

The focuses on convergence and co-production go hand-in-hand; seeking sustainable science-based solutions for addressing real-world, rapid changes across the Arctic requires working closely with Arctic peoples. They are the residents, rightsholders, and original knowledge keepers and stewards of the Arctic. Such collaborative research is extremely challenging, taking place at the interface of diverse cultures, institutions, knowledge systems, and values. NNA has laid bare the complexity of co-production and the challenges associated with balancing, on the one hand, convergence research being led by largely university-based academic scientists and, on the other, the interests of Arctic communities who are addressing the systemic, day-to-day challenges of climate change, while also fighting for self-determination.

COMMUNITY CONCERNS AND GLOBAL CHALLENGES

In March 2020, tribal organizations from the Bering Sea region of Alaska (Bahnke et al., 2020) delivered a letter to NSF addressing a range of concerns about the NNA initiative. Some concerns related to researchers directly, for example, their invitations to Indigenous communities to participate in proposed projects with little lead time to plan for meaningful involvement, as well as researchers seeming to lack training and understanding in co-production research. Additional concerns were more at the scale of the initiative itself, highlighting that funded research was often geographically concentrated, leaving some climate-threatened regions largely unaddressed. In general, there is recognition that NSF miscalculated the extent that Arctic researchers lacked fundamental understanding of what co-production of knowledge means and looks like in practice (Stone, 2020).

When the onslaught of the COVID-19 pandemic disrupted scientific research globally in the winter of 2020, NNA researchers were forced to cease or greatly limit travel and in-person collaboration. This took a high toll on those projects at the early stages of building partnerships with Arctic communities. Then, in early 2022, the Russian invasion of Ukraine swiftly brought new geopolitical realities to international research in the Arctic. Nearly a dozen NNA research projects with ongoing or planned research with partners in Russia were forced to either pause or substantially reorient their efforts. While the fall-out from the war is still unfolding across the world economically and politically, many individuals and communities with ties to the Russian Arctic and its peoples (e.g., those residing along the transboundary waters of the Bering Strait; see Figure 1) are experiencing this tension in unique ways. The feasibility of maintaining meaningful connections with trusted colleagues, friends, and family members is now in question.

A SHIFT TOWARD CO-LEARNING

The launch of the NNA initiative coincided with a period of changing social awareness, especially in terms of acknowledging colonialist structures as well as greater recognition of tribal sovereignty and Indigenous self-determination (e.g., see the 2021 US Presidential *Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships,* https://www.whitehouse.gov/briefing-room/presidential-

FIGURE 1. *The Arctic Arc* was constructed in 1988 by Joseph Senungetuk and David Barr on the mountain side at Kiŋigin (Wales, Alaska) overlooking the Bering Strait toward Russia. The sculpture includes opening wooden hands, joined at the wrist, releasing a bird to take flight across the Strait. It represents peaceful relationships between the Alaskan and Chukotkan Inuit, recollecting the deep historical trading and family ties across the Strait. Created at a time of heightened international tension during the Cold War, it is just as meaningful and relevant in 2022. *Photo credit: Matthew Druckenmiller*

actions/2021/01/26/memorandum-on-tribal-consultation-and-strengthening-nation-to-nation-relationships/). Individuals and institutions across the United States and the globe, including academic institutions, are experiencing a deep introspection toward uncovering and understanding issues of systemic inequalities. In an Arctic context, this calls for greater awareness regarding Indigenous peoples' complex and collective historical traumas associated with colonization, including the forced loss of language.

The COVID-19 pandemic has underscored the need to recognize the deep-rooted influence that past diseases have had across the Arctic. It has shed a light on Arctic researchers' dependencies in partnering with Indigenous communities and gaining access to their traditional Arctic homelands and waters (Petrov at al., 2020). Importantly, COVID-19 has also set the stage for sustained and consequential discussions regarding how Arctic research can more equitably partner with Indigenous communities and knowledge bearers. Petrov at al. (2020) present the pandemic as an opportunity for pause and reorienting, especially in terms of how we value and invest in local science infrastructure and training our next generation of scientists in co-production of knowledge.

Researchers are increasingly aware that the true values and priorities within a project are reflected in the project's budget. Within co-production of knowledge research, Indigenous knowledge holders must be fairly compensated for their time and contributions. Further, there is growing attention toward Indigenous knowledge sovereignty, which recognizes and reaffirms that Indigenous peoples maintain power over how their knowledge is shared, documented, and used. There are calls for academia to shift away from the narrow value system built around citations and publication impact factors toward a more inclusive view of scientific impact, for example, one that values community engagement, science communication, and recruitment, mentorship, and retention of researchers from diverse backgrounds (Davies et al., 2021).

Awareness, good intentions, and careful planning alone are not enough to develop more equitable research practices. Across the NNA initiative, projects are creating Indigenous, Elder, or community member advisory boards as one way to help projects meaningfully engage and address Arctic community concerns. Others are beginning to explore the role of project evaluation, drawing on both western and Indigenous evaluation methodologies. While these are important steps, it is also important that Indigenous institutions or knowledge holders lead research themselves; many see this as critical to advancing co-production of knowledge on a larger scale.

The NNA initiative has ushered in a new period of research in the Arctic—one where there is greater emphasis on co-production of knowledge and where research and researchers are held accountable regarding whether their work is benefiting Arctic peoples. NNA is advancing place-based and applied research in the North, but its broader value may prove to be through the impetus created for researchers and Indigenous peoples to learn together (Figure 2). This co-learning to improve communication and build cultural awareness is a critical first step toward co-production.

In 2021, the NNA Community Office was initiated to provide coordination and assistance to the funded NNA project teams, their research partners, and to anyone interested in

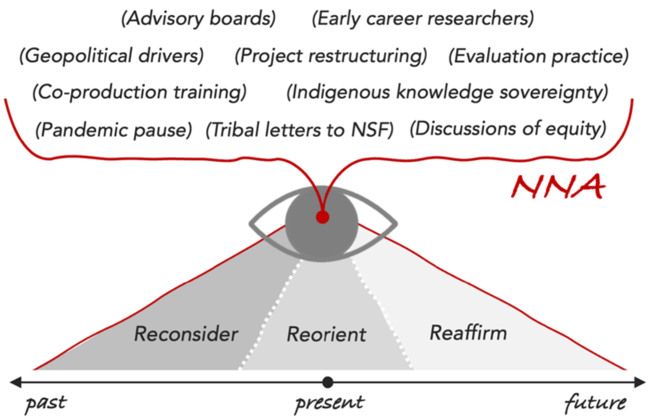

FIGURE 2. Conceptual depiction of the Navigating the New Arctic (NNA) initiative as a space of learning and a focal point for reconsidering historical inequalities, reorienting research projects in the present, and reaffirming commitments to future research practices that support co-production of knowledge and Indigenous self-determination.

applying for or partnering in future NNA research. Its overall goal is to support the NNA initiative in achieving greater benefit to Arctic communities and to societies worldwide. In short, the NNA Community Office exists to support co-learning and appreciation for relationality across the Arctic system (Figure 3).

REFRAMING THE "NEW ARCTIC"

The phrase "New Arctic" emphasizes the new climate and environmental realities facing the Arctic; it represents the new societal challenges that are emerging, setting the focus for convergence research. Yet, for some Arctic people, the phrase has instead reinforced western science's exploration and discovery mentality that can be at odds with respecting Indigenous peoples' sovereignty, stewardship, and historical presence within their lands and waters.

There is opportunity to reframe the "New Arctic" as an invitation to develop relationships of trust and reciprocity and to work together to address the climate crisis. Success in aligning scientific priorities with the well-being of the Arctic and its peoples starts with clearly defined shared goals, patience, and creative approaches to building and nurturing relationships (Ernakovich et al., 2021).

It has been said by Yup'ik Elders that the world is changing, following its people. I have heard this shared in the context of how improper human behavior toward one another and the environment is driving the climate and environment to change. But I believe the phrase is equally true when considering the transformative force that is generated through working together.

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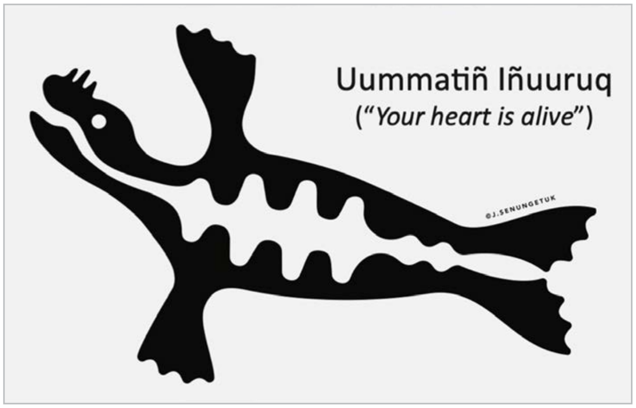

FIGURE 3. This NNA Community Office logo was designed and gifted by Joseph Senungetuk, and was adapted from his ancestral memory of an ancient Iñupiaq artwork. The seal holds traditional knowledge of the lands and waters that sustains its life, but it also offers its life as a gift to the hunter. Joe utilized an ancient art technique from his ancestral memory that depicts the seal's insides, portraying its true form. Its encapsulating phrase, *Uummatiñ Iñuuruq* (offered by Martha Senungetuk), in Iñupiaq translates to "your heart is alive"—a reminder for scientists to see their humanity and values as guiding resources for their research when partnering with Arctic peoples. Visit this video (https://youtu.be/yttNue2EEBI) for the story of the seal design.

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SIDEBAR > THE YUP'IK ATLAS

MAKING HISTORY IN SOUTHWEST ALASKA

By Ann Fienup-Riordan

In 2007, the Calista Elders Council (now Calista Education and Culture, CEC) began a three-year US National Science Foundation (NSF)-funded project to document the history and oral traditions of the Yup'ik people of Nelson Island, located on the Bering Sea coast of southwest Alaska. One project focus was place names, and by 2010 we had recorded over 600 names, including old village sites, rivers, lakes, mountains, and ocean channels. That same year, I gave a presentation on our Nelson Island place name effort at a workshop hosted by the Exchange for Local Observations and Knowledge in the Arctic (ELOKA) project, recently funded by NSF's Office of Polar Programs. Following the presentation, project lead Peter Pulsifer suggested that ELOKA might be able to help CEC share these names using the Nunaliit Atlas Framework, open-source software for making interactive maps that ELOKA was then in the process of testing.

The next step was for Pulsifer to travel to Bethel, Alaska, and to describe the proposed place name Atlas to CEC's Yup'ik Elder Steering Committee. Along with discussing how place names could be displayed, a question was posed regarding who should be the intended Atlas audience. Should the Atlas be password protected and open only to Nelson Island community members? Should it be open only to residents in southwest Alaska? Or should it be open globally on the worldwide web? The unanimous response of this group of Yup'ik-speaking elders was that these names were something everyone should know. Yup'ik youth needed to know the names to keep them safe in a changing environment. Equally important, non-Natives needed to know the names. As CEC elder Martin Moore declared, the names were proof that every square inch of land in southwest Alaska had been walked on by his ancestors.

Over the last decade, funded by both NSF and the US Fish and Wildlife Service, CEC has continued a string of regional oral history projects, documenting more than 4,000 place names along the lower Yukon River, the middle Yukon River, and the lower Kuskokwim coast; in the Akulmiut/Tundra Village area; and most recently along the middle Kuskokwim River (**Figure 1**). Along with adding names, ELOKA staff taught CEC summer interns how to add a Hover Sound to each name, so that Atlas visitors can hear the name as well as view its location. The powerful Nunaliit platform has also allowed staff and interns to add stories—both traditional tales and historical accounts of bow-and-arrow warfare—to selected sites. Photos and short videos have also been added, and (at the request of our Elders Steering Committee) GPS locations of sites are available to download region by region, which is especially valuable to local search and rescue teams. Most recently, translated text has been added so that visitors can view the Atlas in either Yup'ik or English.

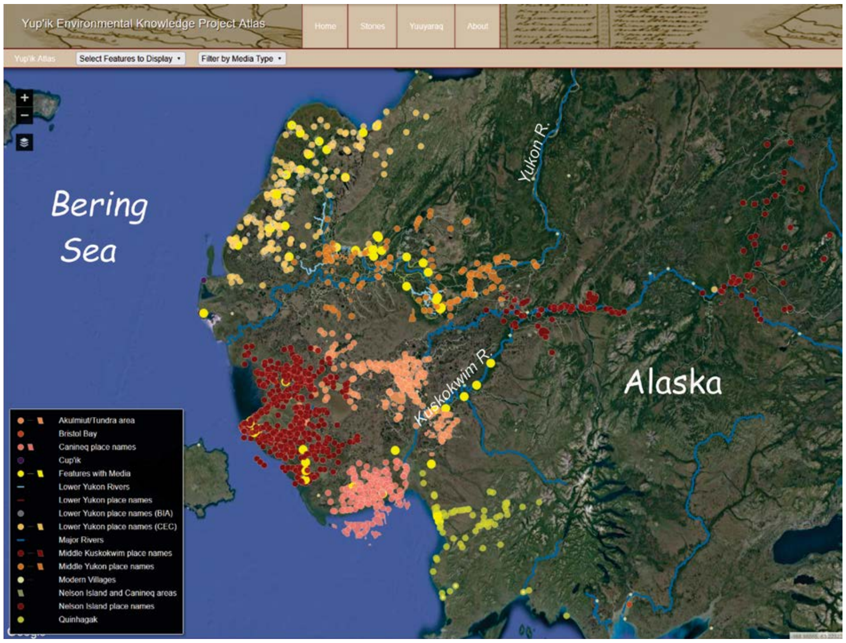

FIGURE 1. Home page of the Yup'ik Atlas (http://eloka-arctic.org/communities/yupik/) developed by the Exchange for Local Observations and Knowledge in the Arctic project in collaboration with the Calista Elders Council (CEC, now Calista Education and Culture).

In 2018, a new Yuuyaraq module was added to the Atlas as part of the Yuuyaraq (Yup'ik way of being) ninth-grade life-skills curriculum CEC developed in collaboration with the Lower Kuskokwim School District, which serves 28 schools in southwest Alaska. As part of the curriculum, students not only learn how to use the Atlas, they also are given access to the staging Atlas where

FIGURE 2. Ray Waska, Peter Moore, and Mark John at Nanvaruk on the lower Yukon River, August 2011. *Photo credit: Ann Fienup-Riordan*

they can add place names, stories, photos, and videos from their own areas and experiences. With the skeleton of the Atlas in place, the potential to add new layers of information is infinite. A module focusing on climate change presently in the works will include "story maps" that allow visitors to scroll over a selected modern village in order to see the shape of the surrounding land in the 1950s.

The new climate module under development will also display an interactive map of the Yukon-Kuskokwim delta. The viewer can grab a slider and drag it back and forth to compare two layers that represent different time periods. For example, one map will compare historically derived freeze-up data for 2000–2009 to modeled data at 20-year intervals. Other maps will compare historically derived data to projected delays in fall freeze-up, changes in average summer precipitation, and projected increases in average fall temperatures. This module will be particularly valuable, as it highlights changes projected to occur in numerous coastal locations already present in the Atlas.

In 2019, the ELOKA team, including Pulsifer, Noor Johnson, and Matt Druckenmiller, visited Bethel once again, both to discuss Atlas progress with the Elders Steering Committee and to provide training to Lower Kuskokwim School District staff. Growing the Atlas in a region of Alaska with low bandwidth, limited technology, and exorbitant internet costs has been challenging. Yet savvy students have used their iPhones to record elders sharing aspects of a lived tradition still highly valued in their communities (**Figure 2**).

Many have observed that it is traditional among Arctic peoples to use the best technology available. The Yup'ik Environmental Knowledge Project Atlas (https://eloka-arctic.org/communities/yupik/atlas/) is state-of-the-art, with capacity to add audio, video, text, and photos to any single point or line. Yet in many areas it is a skeleton without flesh. The goal of our most recent project is to work with an array of partners—local tribal governments, school districts, statewide institutions, and national and international institutions—to build on what ELOKA has created, not from the outside in but rather beginning at the village level, to continue developing a vehicle to share Yup'ik history from the Yup'ik point of view.

Villages today struggle to find relevance socially, economically, and culturally. From the beginning, Yup'ik elders and community members have advocated for creating both CEC-sponsored books (many authored and edited by myself and my co-worker Alice Rearden) and the ELOKA Atlas as ways to educate their youth, as well as the larger world, about Yup'ik language and traditional knowledge. In 2009, Nelson Island leader Paul John compared the effect of our documentation efforts to that of the election of President Obama. He said, "If white people see these books, they will think, 'These Yup'ik people evidently are knowledgeable and know how to take care of their own affairs through their traditional ways.' Like the African-American who has become president, our young people will be able to independently practice their way of living."

Our work with the Yup'ik Atlas seeks to make Paul John's vision a reality—working with elders and youth to present Yup'ik history in new formats that will allow them to sustain these living traditions in a global world. Elders maintain that if youth not only know their history and take pride in it but also have a role in creating it, their future will be brighter.

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SIDEBAR > RESEARCH NETWORKING ACTIVITIES SUPPORT SUSTAINED COORDINATED OBSERVATIONS OF ARCTIC CHANGE

By Craig Chythlook, Margaret Rudolf, Maureen Biermann, Hajo Eicken, and Sandy Starkweather

Rapid Arctic environmental change requires improved collaboration across observing activities that support adaptation and response from local to pan-Arctic scales. The Research Networking Activities in Support of Sustained Coordinated Observations of Arctic Change (RNA CoOBs), in partnership with the Food Security Working Group (FSWG), supports an Indigenous-led project on food security. These efforts tie into the broader goals of the Sustaining Arctic Observing Networks (SAON) Roadmap for Arctic Observing and Data Systems (ROADS). SAON is an open initiative of the International Arctic Science Committee and the Arctic Council, uniting Arctic and non-Arctic countries and Indigenous, regional, and global organizations that support improved observing network development and integration. SAON has been advancing a partnership development framework under ROADS that adds value to different observing activities by providing common context and identifying shared goals.

SAON, drawing on such forums as Arctic Observing Summits (AOSs) and Arctic Science Ministerials, has begun to quantify the shared societal benefits that sustained observations of a changing Arctic provide to Arctic and non-Arctic countries as a first step in the ROADS process. Also, SAON's Committee on Networks has assembled inventories of existing observing activities. ROADS is leading the identification of variable sets that address high-priority information needs. From such shared Arctic variables—a concept that recognizes both strengths and limitations of essential variable approaches used by global networks (Starkweather et al., 2021)—flow enhanced requirements that help guide the design of the evolving observing and data systems in support of broadly shared benefits. Four key principles guide this work: (1) Indigenous peoples' equitable partnerships and funding for their active participation is critical to ROADS; (2) all aspects of the ROADS process should support broadly shared benefits from observing and data systems; (3) the ROADS process should complement and integrate, without duplication, planning approaches used by existing networks (regional to global), activities, and projects; and (4) ROADS should support stepwise development through a flexible and evolving structure that allows grassroots identification of themes, infrastructures, and areas of regional interest (Starkweather et al., 2021).

In collaboration with the FSWG, RNA CoObs supports this process with a focus on the Pacific Arctic sector. It seeks to: (1) capture requirements for a set of shared Arctic variables with the FSWG and communities in the region; (2) collaboratively develop an engineering design for observing activities, drawing on observing system simulation to help guide this process; (3) design or adapt information infrastructure to share data and information products with users; and (4) build a community of practice cutting across regions, disciplines, and knowledge systems. This work is meant to explore how an internationally coordinated roadmap for Arctic observing can be developed.

The FSWG views food security and food sovereignty through an Indigenous lens, seeking to weave health and wellness into every aspect of an observation system (AOS, 2020). Equitable inclusion of Indigenous peoples must be realized both at the advising and subject matter expert levels throughout ROADS to be successful. The FSWG helps ensure an inclusive process and maintains food security as a central concept within observing network planning. Three Indigenous liaisons assist in this process by facilitating and coordinating community outreach, international participation, and development of ethical guidelines and protocols. Guided by AOS 2020 recommendations, the liaison team connects RNA CoObs, ROADS teams, and rural and Indigenous community members to support community-driven research and monitoring focused on health and wellness, one of six food security dimensions laid out by the Inuit Circumpolar Council's Alaskan Inuit Food Security Conceptual Framework (Inuit Circumpolar Council-Alaska, 2015).

The liaison team works with the FSWG and RNA CoObs to address SAON goals for creating a roadmap to a well-integrated Arctic Observing System, promoting free and ethically open access to all Arctic observational data, and ensuring sustainability of Arctic observing by integrating a western framework with the social, economic, spiritual, and cultural needs of Indigenous peoples and others within the Arctic. These goals and the RNA framework were created outside the Indigenous community, and the FSWG is doing its best with a framework that is fundamentally at odds with what many communities, organizations, and tribes continue to request. This work enriches our understanding of how to co-produce variables (**Figure 1**). The FSWG applauds the efforts of SAON, ROADS, and RNA CoObs, but recognizes concerns raised about the reductionist approach inherent in a shared Arctic variable and about how best to make use of research and observation efforts to assist in meeting Inuit

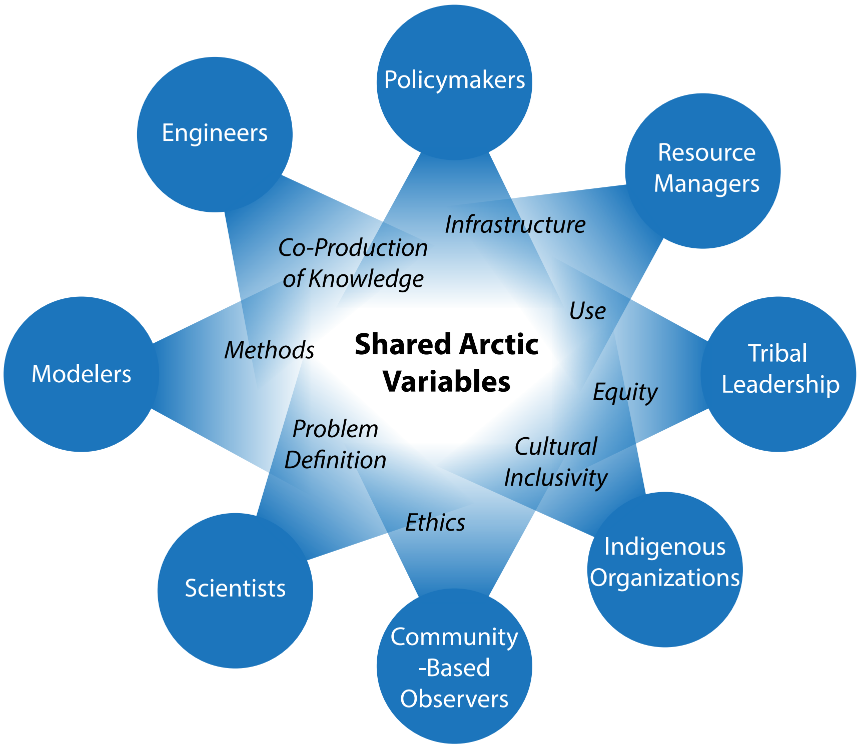

FIGURE 1. Schematic depiction of how Research Networking Activities in Support of Sustained Coordinated Observations of Arctic Change and the Roadmap for Arctic Observing and Data Systems process rely on shared Arctic variables as a starting point for discussions about improved observing network development and integration. The outer circles represent the various groups of actors that participate in and rely on Arctic observations. The key attributes, in italics, are what the actors bring to the process of improving observing network development and integration.

goals for securing food sovereignty and food security. This requires overcoming challenges to effective participation in policy and regulatory bodies over traditional resources and addressing a lack of acceptance and acknowledgment of Indigenous knowledge and management practices that have kept Inuit in the Arctic in balance with their ecology since time immemorial.

An important step in helping reach SAON goals through the FSWG is recognizing that representation and perspectives of Indigenous academics, scholars, and knowledge holders are key to ensuring the ROADS process is an Indigenous-led project. Another important step in meeting collective goals is building capacity within rural communities by funding their participation and current projects that align with the FSWG.

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SIDEBAR > CO-PRODUCTION OF SEA ICE KNOWLEDGE IN UUMMANNAQ BAY, GREENLAND

By Jonathan Ryan, Parnuna Egede Dahl, and Brigt Dale

Sea ice formation in the Arctic Ocean has long fascinated scientists for its impacts on ocean circulation, temperature-albedo feedbacks, and weather in the mid-latitudes. However, before scientists started studying sea ice, Indigenous peoples and local communities whose livelihoods depended on it generated a vast body of sea ice knowledge (Krupnik, 2010). Indigenous and local knowledge systems have their own contextual frameworks, methodologies, and validation processes that differ from those of scientific knowledge (Petersen, 2010). Now that sea ice is declining, scientists and Arctic residents share a common concern about the future of sea ice and are becoming increasingly interested in each other's study methods (Huntington et al., 2022). Importantly, scientists have recently begun to respond to the call from Arctic Indigenous Peoples (Arctic Council Permanent Participants, 2018) and the Arctic Council (2018) for their engagement with and recognition of the qualitative contributions other knowledge systems can offer scientific knowledge production.

Recognizing the power of different knowledge systems and acknowledging the history of extractivist practices in science on Indigenous lands, our US National Science Foundation funded Navigating the New Arctic project aims to study sea ice in ways that provide value to both scientists and residents of Uummannaq Bay, Greenland (70°40'N, 52°07'W). We are involving local residents and institutions at all stages of the project, from planning to dissemination. The variety of research methods being used includes satellite and airborne remote sensing, quantitative modeling, qualitative approaches (including ethnographic and semi-autobiographical storytelling), and community-based monitoring, all of which are co-produced, supported, and guided by the residents of Uummannaq Bay. Our focus on knowledge co-production ensures that findings of our project may be useful for local planning and policy development as well as for increasing a sense of personal and community well-being and sense of security through a strengthening of knowledge about one's surroundings.

The Uummannaq Bay region is home to around 2,229 people living in eight settlements (Statistics Greenland, 2021). These communities exemplify some of the many changes and developments, transitions, and stressors affecting Greenlanders and their environment, including regional population declines, socioeconomic and political transformations, and increased hazards. In particular, the region has undergone substantial environmental change in the twenty-first century. Annual surface air temperatures and subsurface ocean temperatures warmed by nearly 2°C between 1995 and 2010 (Holland et al., 2008; Howat et al., 2010). In 2015, residents reported that the sea ice "is gone around May" and "doesn't get really thick" in comparison to past decades (Baztan et al., 2017). These environmental changes have serious impacts on the Uummannaq Bay communities, where subsistence production continues to play a considerable role in material support and cultural identity.

In spring 2019, a project team visited Uummannaq for the planning stage of our project. The goal was to learn about which aspects of sea ice most interested the local residents and how we could make our scientific knowledge more relevant. We started by presenting the project to local hunters, fishers, and youth. Using maps of Uummannaq Bay that we printed out from high-resolution Sentinel-2 satellite imagery, youth and elders alike identified their settlements as well as hunting and fishing spots. We also presented graphs showing the timing of sea ice breakup in Uummannaq Bay over the past 20 years based on our preliminary remote sensing analysis. We learned that our scientific results were often corroborated by people's memories. For instance, people generally agreed that the sea ice melted early in 2016 and did not form around Uummannaq in 2005. This early-stage meeting made our intentions clear and increased opportunities for feedback on our research.

Overall, it was clear that residents are concerned about the dwindling sea ice. We learned, however, that there are economic incentives toward earlier sea ice breakup. One of the major findings of our field trip was discovering that sea ice around the town of Uummannaq is deliberately broken up almost every year so that cargo ships can export fish stored in the fish factory's freezers. The largest economic activity in Uummannaq, fishing occurs almost year-round except during breakup and freeze-up when the ice is unsafe. At some point in spring, the freezers are full, and no one can sell additional fish to the factory. On May 10, 2019, an ice-strengthened vessel arrived to initiate the breakup of sea ice in the fjord so that cargo ships could enter Uummannaq harbor. We had not anticipated the human intervention on sea ice breakup, and it provides a cautionary lesson for researchers—without being in Uummannaq, we could not have known about the actual cause of sea ice breakup in 2019 and learned how frequently this human intervention occurs. Our scientific knowledge is useful to a point, but Indigenous knowledge and local knowledge are prerequisites for fuller understanding of an environmental system.

FIGURE 1. (above) Sled dog team returning to Uummannaq on sea ice. (right) A resident of Uummannaq examines satellite images of sea ice. *Photos courtesy of Sarah Cooley*

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MONITORING ALASKAN ARCTIC SHELF ECOSYSTEMS THROUGH COLLABORATIVE OBSERVATION NETWORKS

By Seth L. Danielson, Jacqueline M. Grebmeier, Katrin Iken, Catherine Berchok, Lyle Britt, Kenneth H. Dunton, Lisa Eisner, Edward V. Farley, Amane Fujiwara, Donna D.W. Hauser, Motoyo Itoh, Takashi Kikuchi, Stan Kotwicki, Kathy J. Kuletz, Calvin W. Mordy, Shigeto Nishino, Cecilia Peralta-Ferriz, Robert S. Pickart, Phyllis S. Stabeno, Kathleen M. Stafford, Alex V. Whiting, and Rebecca Woodgate

November 2021 deployment of a Chukchi Ecosystem Observatory (CEO) mooring in the northeast Chukchi Sea. This mooring's instrumentation includes a time series sediment trap, a passive acoustic underwater sound recorder, and data loggers to record temperature, salinity, pressure, pH, and dissolved oxygen. *Image credit: Seth Danielson*

ABSTRACT. Ongoing scientific programs that monitor marine environmental and ecological systems and changes comprise an informal but collaborative, information-rich, and spatially extensive network for the Alaskan Arctic continental shelves. Such programs reflect contributions and priorities of regional, national, and international funding agencies, as well as private donors and communities. These science programs are operated by a variety of local, regional, state, and national agencies, and academic, Tribal, for-profit, and nongovernmental nonprofit entities. Efforts include research ship and autonomous vehicle surveys, year-long mooring deployments, and observations from coastal communities. Inter-program coordination allows cost-effective leveraging of field logistics and collected data into value-added information that fosters new insights unattainable by any single program operating alone. Coordination occurs at many levels, from discussions at marine mammal co-management meetings and inter-agency meetings to scientific symposia and data workshops. Together, the efforts represented by this collection of loosely linked long-term monitoring programs enable a biologically focused scientific foundation for understanding ecosystem responses to warming water temperatures and declining Arctic sea ice. Here, we introduce a variety of currently active monitoring efforts in the Alaskan Arctic marine realm that exemplify the above attributes.

INTRODUCTION

The Pacific Arctic region (PAR) is important both regionally and globally. It supports the region's climate functions, ecosystems, and social systems, all of which are inexorably linked to the Indigenous communities and the physical, chemical, and biological functioning of the Bering, Chukchi, and Beaufort Seas. These systems derive their regional structures and characters as direct consequences of ocean currents (Woodgate and Peralta-Ferriz, 2021) that deliver heat, nutrients, and carbon northward across the PAR (**Figure 1**). Within the region, the Alaskan Arctic marine environment has undergone widespread warming in recent decades (Danielson et al., 2020), and the area's decreasing sea ice is associated with ecological responses and adaptations by Arctic coastal residents (Grebmeier et al., 2006; Huntington et al., 2020; Hauser et al., 2021). Monitoring this entire area for all responses is beyond the scope of a single observational effort, yet much may be achieved by combining information gathered by different programs, especially long-term in situ studies. Together, such efforts yield a pan-region interdisciplinary synergy. In this article, we aim to demonstrate the breadth of existing monitoring efforts in the US Arctic, which extends from the eastern Bering Sea shelf to the Beaufort Sea shelf. The long-term observation programs we introduce provide time-series data that are critical for quantifying ecosystem changes, anticipating future conditions, and understanding linkages between loss of sea ice, alterations in oceanographic and biogeochemical conditions, and effects on people and all trophic levels from microbes to apex predators.

One of the pressing needs for evaluating climate change impacts on the marine ecosystem in the Arctic (and globally) is the need for sustained observations of change. Biological observations cannot be automated to the same extent as many physical measurements and as a result, there is far less scientific documentation of how biological systems are changing and/or adapting due to environmental changes. Sustained investment of public funds that supports ongoing monitoring efforts, along with the use of these data in resource management decisions, provides an indication of their societal importance.

Here, we describe a selected set of 17 independently funded, organized, and operated long-term monitoring programs (**Table 1**) that, while formally uncoordinated as a whole, in practice represent a rich, ongoing, and frequently updated suite of data collections that together characterize many aspects of the Alaskan Arctic marine systems. We include only long-term, in situ observational monitoring efforts. Together, they document aspects of ocean and ice physics, nutrient and carbonate chemistry, and all trophic levels. Some efforts make observations only in the open water season while others continue year-round. Our selection represents a diversity of funding agencies, geographic coverage, and observing techniques. These efforts document environmental and ecosystem structure and change across spatial scales as large as the expanse of the Bering-Chukchi-Beaufort shelves and timescales spanning hours to decades. They include vessel-based surveys, autonomous platforms, and coastal community-based efforts. The latter provide a unique, invaluable, and much longer-term perspective on system change based on deep insight into the structure and functioning of the Arctic system by drawing on long-developed local traditional Indigenous knowledge (Eicken et al., 2021).

This discussion does not include off-shelf studies and individual process studies (typically one to three years of fieldwork) and larger process-oriented research programs (typically three to ten years of fieldwork). Nevertheless, process studies play a key role in advancing our understanding of the ecosystem, provide baseline data that underlie ongoing monitoring, and inform monitoring priorities and approaches. In turn, the monitoring programs help define questions that require the attention of new process studies. Prominent ecosystem-focused PAR process study programs conducted in recent decades include, but are not limited to, the following efforts (acronyms and field years are given in parentheses): Processes and Resources of the Bering Sea Shelf (PROBES; 1976–1982), Inner Shelf Transfer and Recycling (ISHTAR; 1983–1989), Western Arctic Shelf-Basin Interactions (SBI; 2002–2006), Bering Ecosystem Study (BEST; 2007–2011), Bering Sea Integrated Ecosystem Research Program (BSIERP; 2007–2011), Russian-America Long-term Census of the Arctic

(RUSALCA; 2004–2012), Chukchi Sea Environmental Studies Program (CSESP; 2008–2015), and Arctic Integrated Ecosystem Research Program (Arctic IERP; 2017–2019).

Although independently executed, each of the monitoring programs described here benefits from inter-program coordination that includes community outreach, planning, leveraged field logistics, data sharing, and collaborative data analyses. Avoiding marine domain conflict with subsistence hunters is a top priority for Alaska-region scientific field efforts, and clear and open communication with subsistence harvest co-management groups and village tribal councils is critical for maintaining productive and respectful relationships. Scientific monitoring benefits from local co-production of knowledge partnerships carried out with Indigenous coastal communities (Hauser et al., 2021). Co-management group meetings, such as those of the Alaska Eskimo Whaling Commission, help researchers communicate with community representatives. Research coordination is also fostered by the Alaska Marine Science Symposium (AMSS), a conference held annually in Anchorage that attracts ~1,000 marine researchers and provides a forum for communication across the Pacific subarctic and Arctic research communities. In addition to other national and international scientific meetings, meetings of the Pacific Arctic Group (PAG), the North Pacific Marine Science Organization (PICES), and the Ecosystem Studies of the Subarctic and Arctic Seas (ESSAS) help coordinate PAR field research and scientific collaborations on an international basis.

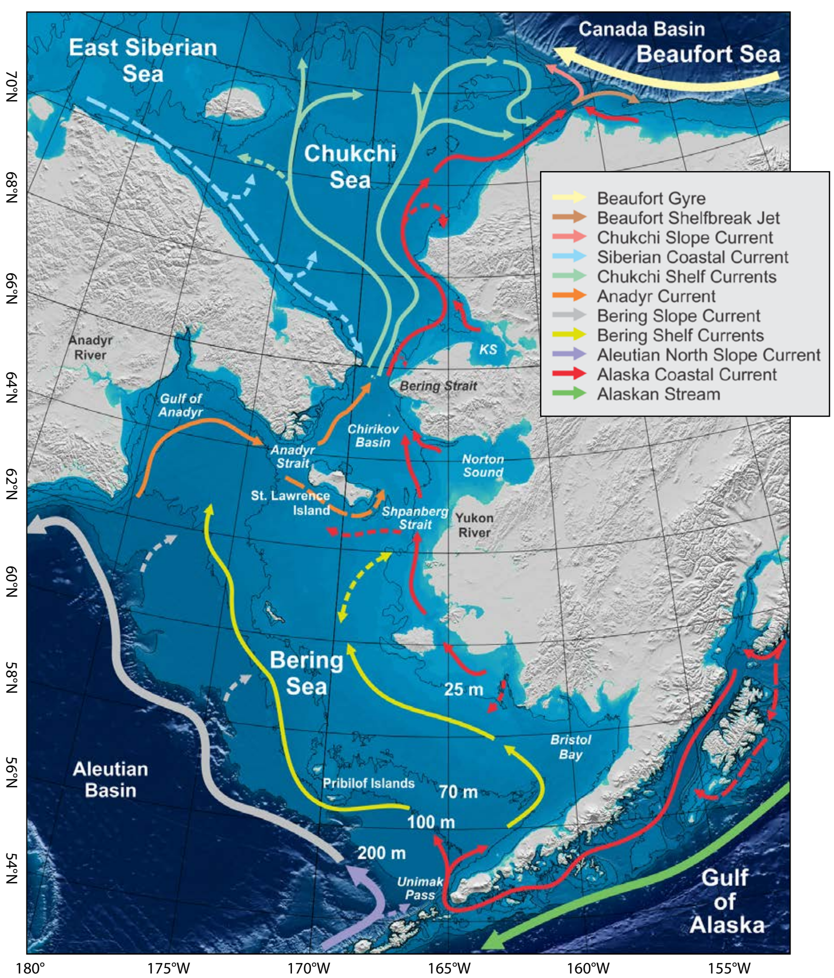


FIGURE 1. Map of the region typically called the Pacific Arctic, showing place names and an idealized depiction of the mean oceanic currents. KS = Kotzebue Sound.

While many monitoring programs (Table 1) have different objectives and geographical foci, we find commonality in approaches, motivations, and innovations. One means of assessing changes in the marine environment is to examine the distribution of flora and fauna that are directly influenced by environmental changes. In the Arctic, marine mammals and seabirds have been proposed as ecosystem sentinels of change (Moore and Kuletz, 2019), and passive acoustic sampling has proven to be a robust means of detecting species-specific presence of vocalizing marine mammals throughout the year (Stafford et al., 2021). Similar approaches are applied to planktonic, pelagic, and benthic communities resolved by time-series sediment traps, water samplers, photographic and active acoustic imaging systems, nets, and benthic grabs, cores, and trawls (see citations later in the text). Specific results and additional references for the programs discussed below and listed in Table 1 are included in the online supplementary materials.

COMMUNITY-BASED AND COASTALLY FOCUSED PROGRAMS

Coordinated community-based observing efforts, such as the Alaska Arctic Observatory & Knowledge Hub (AAOKH), provide distributed, sustained, long-term, and holistic observations of shifting environmental conditions in coastal Arctic Alaska from an Indigenous perspective (Figure 2a). Iñupiaq people in northern Alaska have been monitoring coastal changes for millennia and are among the first to experience and detect changes in the environment, given their deep connections to place and integral reliance on traditional marine and coastal resources. AAOKH is an observing network whose primary goal is to provide communities with the tools, resources, and scientific support to share their expertise and Indigenous knowledge through observations of changing coastal conditions and associated impacts on their access to traditional marine resources. Iñupiaq local experts, termed "observers," regularly document environmental conditions and community events, including weather; sea ice or ocean conditions and travel safety; coastal erosion; river freeze-up and breakup; and marine or coastal fish, bird, and wildlife sightings and harvests. Some observers also seasonally measure aspects of coastal physical (e.g., temperature, salinity) and biological (e.g., chlorophyll *a* fluorescence) oceanographic or landfast sea ice conditions (e.g., ice mass balance, ice edge location, sea ice thickness).

TABLE 1. Selected in situ long-term observing systems active in the Alaskan Arctic in recent years, along with program type, year of first sampling, observational focus, and funding sources. Most programs listed here have gaps of one year or more since their beginning.

PROGRAM	START YEAR	MONITORING FOCUS	FUNDING SOURCES
AFSC Bering Sea and Chukchi Sea Bottom Trawl Surveys	1982	Standardized bottom trawl surveys of groundfish and shellfish.	NOAA Fisheries
Bering Strait – Pacific Gateway to the Arctic	1990	Year-round moorings monitoring water properties and transports of volume, heat, freshwater, and ice through the Bering Strait.	NSF, ONR, NOAA-RUSALCA, AOOS
EcoFOCI: NOAA Ecosystems and Fisheries Oceanography Coordinated Investigations	1990	Moorings (1995 Bering, 2010 Chukchi), drifters and shipboard measurements (1990) to improve understanding of ecosystem dynamics and to inform management of living marine resources.	NOAA (OAR, Fisheries, OER), plus NPRB, AOOS, NSF, BOEM, NASA
Native Village of Kotzebue Environmental Program	1998	Ecosystem functioning, bearded seals, Indigenous and Western science co-production of knowledge.	USEPA, GBMF, USNPS, CP, USFWS, NSF, NFWF, NOAA, NMFS, NMML, USGS, SEP, NWAB, WCS, NPRB, UAF
R/V *Mirai* Arctic Ocean cruises	1998	Oceanographic conditions associated with sea-ice and sea-ice loss and their impacts on the marine biogeochemical cycles and ecosystems.	MEXT
JAMSTEC Barrow Canyon Mooring Experiment	2000	Year-round moorings monitoring volume, freshwater, and heat transport of Pacific water into the Arctic basin	MEXT
BASIS and IES: Bering Arctic Subarctic Integrated Survey and Arctic Integrated Ecosystem Survey	2002	Biological and physical oceanographic conditions and ecological information on pelagic and benthic fish and invertebrate communities.	NOAA, plus AYKSSI, YRDFA, NPRB, AKSSF, ADFG, CIAP, BOEM, USFWS
WABC: Western Arctic Boundary Current Monitoring	2002	Year-round moorings monitoring physical and biogeochemical properties for understanding the fate and impacts of Pacific water in the Arctic.	NSF-OPP
USFWS seabird at-sea surveys	2006	Temporal and spatial patterns of marine birds in Alaska's oceans, and examination of changes in the offshore abundance and distribution of seabird communities.	USFWS, BOEM, NPRB
ALTIMA: Arctic Long-Term Integrated Mooring Array	2007	Year-round moorings monitoring the distribution and timing of marine mammals.	BOEM, ONR, NMFS
Passive acoustic systems in Bering Strait, Chukchi Sea, and Beaufort Sea	2008	Moorings (since 2008) and gliders (since 2013) documenting inter-seasonal and interannual presence of vocal marine mammals, changes through time, and relation to the physical environment.	NSF, NOAA, NOPP, ONR, NPRB, AOOS
HFR: High Frequency Radar surface current mapping	2009	Real-time mapping of ocean surface currents in the open water season. Northeast Chukchi measurements began in 2009. The Bering Strait system is in the process of being installed.	AOOS; past support from BOEM, SEP, CAASP, CIAP, CIMES
DBO: Distributed Biological Observatory	2010	Biological response to environmental changes being observed in the Pacific Arctic via physical, chemical, and biological trophic measurements, with a primary focus on high benthic biomass hotspot sites.	NSF AON, NOAA ARP
CEO: Chukchi Ecosystem Observatory	2014	Year-round moorings monitoring all trophic levels and the physical and biogeochemical environments.	AOOS, NPRB, ONR, NOPP (NOAA/BOEM)
AMBON: Arctic Marine Biodiversity Observing Network	2015	Arctic biodiversity data across all trophic levels, from microbes to whales.	NOPP: BOEM, NOAA, NASA, and initially SEP; ONR
AAOKH: Alaska Arctic Observatory and Knowledge Hub	2016	Sustained, long-term, and holistic observations of shifting environmental conditions in coastal Arctic Alaska from an Indigenous perspective.	Community Service Payments to the State of Alaska Dept. of Justice
BLE LTER: Beaufort Lagoon Ecosystems Long-Term Ecological Research Program	2017	Interactions between terrestrial inputs, sea ice dynamics, and ocean exchange that control lagoon ecosystems along the Arctic coast.	NSF-OPP, USFWS, AOOS

Abbreviations: ADFG = Alaska Department of Fish and Game. AFSC = NOAA Alaska Fisheries Science Center. AKSSF = Alaska Sustainable Salmon Foundation. AOOS = Alaska Ocean Observing System. ARP = Arctic Research Program. AYKSSI = Arctic Yukon Kuskokwim Sustainable Salmon Initiative. BOEM: Bureau of Ocean Energy Management. CAASP = Collaborative Alaskan Arctic Studies Program. CIAP = Alaska Coastal Impact Assistance Program. CIMES = National Center for Island, Maritime, and Extreme Environment Security. CP = Conoco Phillips. DBO = Distributed Biological Observatory. GBMF = Gordon and Betty Moore Foundation. JAMSTEC = Japan Agency for Marine-Earth Science and Technology. MEXT = Ministry of Education, Culture, Sports, Science and Technology – Japan. NASA = National Aeronautics and Space Agency. NFWF = National Fish and Wildlife Foundation. NMFS = National Marine Fishery Service. NOAA = National Oceanographic and Atmospheric Administration. NOAA ARP = NOAA Arctic Research Program. NOAA OAR = NOAA Office of Oceanic and Atmospheric Research. NOAA OER = NOAA Office of Ocean Exploration and Research. NOAA-RUSALCA = Russian-American Long-term Census of the Arctic. NOPP = National Oceanographic Partnership Program. NMML = National Marine Mammal Laboratory. NPRB = North Pacific Research Board. NSF = National Science Foundation. NSF AON = NSF Arctic Observing Network. NSF-OPP = NSF Office of Polar Programs. NWAB = Northwest Arctic Borough. ONR = Office of Naval Research. SEP = Shell Exploration and Production. UAF = University of Alaska Fairbanks. UIC = Ukpeagvik Inupiat Corporation. USEPA = US Environmental Protection Agency. USFWS = US Fish and Wildlife Service. USGS = US Geological Survey. USNPS = US National Park Service. WCS = Wildlife Conservation Society. YRDFA = Yukon River Drainage Fisherman's Association.

Coordinated and year-round observations from AAOKH observers collectively provide a broad-scale and synoptic view of changing coastal sea ice and ocean conditions, and ultimately impacts, at the coastal community scale (Eicken et al., 2021). Recent themes emerging from AAOKH observations document abrupt changes in landfast sea ice that affect travel safety, shoreline erosion affecting infrastructure, warming ocean and air temperatures, and shifts in wind and weather patterns. AAOKH observers also identify anomalous conditions, such as novel species or shifts in the seasonal occurrence of regular species. Environmental changes are often linked to food security and impacts on traditional lifestyles. The AAOKH network evolved out of a predecessor program called the Seasonal Ice Zone Observing Network (SIZONet), with observations dating as early as 2006 and encompassing several western and northern Alaska communities (Eicken et al., 2014). The shared and ongoing AAOKH-SIZONet database currently includes >8,000 observations that encompass local and Indigenous perspectives of coastal change (Adams et al., 2013).

The Native Village of Kotzebue Environmental Program (NVK EP) facilitates and undertakes research on the ecology of Kotzebue Sound through a combination of Indigenous knowledge and skill sets with western science and scientists using co-production of knowledge approaches (Whiting et al., 2011; Hauser et al., 2021; Mahoney et al., 2021). Research activities have targeted the study of fish and other wildlife species found in Kotzebue Sound, including their health, behavior, and impacts resulting from the rapidly changing climate. NVK EP efforts also focus on ice seals, beluga whales, and sheefish (inconnu); the coastal lagoon system and its relationship to the ecology of the marine ecosystem, with a particular focus on whitefish species; contaminants and nutrients found in species of high subsistence value (e.g., ice seals, sheefish, whitefish); the physical environment of the sound, including sea ice, snow pack, water quality (physical, chemical, and biological), and currents (circulation and hydrographic structure); emergent harmful algal blooms; and the contribution of the Sound to the annual

TABLE 2. Representative observing system successes and insights from the programs listed in Table 1.

PROGRAM	OBSERVING SYSTEM SUCCESSES
AFSC Bottom Trawl Surveys	Annual sampling of groundfish, crab, other invertebrates, acoustic backscatter, and oceanographic data on the eastern Bering Sea shelf.
Bering Strait - Pacific Gateway to the Arctic	Identification of multidecade trends in volume, heat, and freshwater fluxes from the Pacific into the Arctic.
EcoFOCI	Development of the Oscillating Control Hypothesis—a new understanding of ecosystem dynamics in the Bering Sea and differentiation between warm and cold years and implications on the ecosystem. Variability of nutrient flux in the northern Bering Sea and eastern Chukchi Sea.
Native Village of Kotzebue Environmental Program	Increasing visibility of Indigenous-led Arctic research projects, contributing to the promotion of the co-production approach to research.
R/V *Mirai* Arctic Ocean cruises	Arctic Challenge for Sustainability project research activities, including documentation of Arctic marine environmental and ecosystem changes, were published in a special issue of *Polar Science*.
JAMSTEC Barrow Canyon Mooring Experiment	Twenty years of monitoring water transport and property variations of Pacific-origin waters entering the Arctic.
BASIS and IES: Bering Arctic Subarctic Integrated Survey and Arctic Integrated Ecosystem Survey	New insights into benthic community structure (fishes and invertebrates), environmental conditions, harmful algal bloom sampling, ecosystem activity/structure during late summer, condition and relative abundance of small (age-0 and juvenile) fishes prior to winter, seabird species composition, and distribution.
Western Arctic Boundary Current Monitoring	A single strong upwelling event can flux enough heat offshore to melt an area of 1 m thick ice the size of the Beaufort shelf.
USFWS seabird at-sea surveys	During the recent (2017–2019) unprecedented high ocean temperatures, some seabird species and communities shifted northward, while others declined in abundance throughout the area.
ALTIMA: Arctic Long-Term Integrated Mooring Array	Bowhead whales are overwintering farther north in the Bering Sea and Hope basins than in previous years.
Passive acoustic systems in Bering Strait, Chukchi Sea, and Beaufort Sea	Increasing detections of killer whales (*Orcinus orca*) in the Pacific Arctic.
HFR: High Frequency Radar surface current mapping	Development and decade-long use of remote power modules for off-grid real-time mapping of surface ocean currents, revealing structure of flow patterns near Barrow Canyon.
DBO: Distributed Biological Observatory	The northern Bering Sea may be at tipping point of moving the ecosystem to a new state with unknown consequences; also, indication of cold-adapted faunal populations shifting northward.
CEO: Chukchi Ecosystem Observatory	Seasonally resolved depictions of production, export fluxes, and fish and zooplankton abundance and behavior in relation to the physico-chemical environment and its variations.
AMBON: Arctic Marine Biodiversity Observing Network	Changes in diversity and species composition across multiple assemblages in the northeast Chukchi Sea during two contrasting years are consistent with borealization.
AAOKH: Alaska Arctic Observatory and Knowledge Hub	New insights in changing coastal conditions, particularly phenological shifts in sea ice events, novel or unusual wildlife occurrence, and impacts to communities.
BLE LTER: Beaufort Lagoon Ecosystems Long-Term Ecological Research	Biological and physical measurements made during ice cover, ice breakup, and open water provide a much deeper understanding of the strong seasonality of these systems and the role of allochthonous and autogenous sources of carbon to nearshore food webs.

subsistence harvest of the people of Kotzebue (Qikiqtaġruŋmiut).

The Beaufort Lagoon Ecosystems Long Term Ecological Research (BLE-LTER) program is focused on interactions between terrestrial inputs, sea ice dynamics, and ocean exchange that control lagoon ecosystems along the Arctic coast over seasonal to multidecadal timeframes (e.g., Bonsell and Dunton, 2018). This program, which incorporates Indigenous community participation and support, is broadly relevant to understanding ecosystem dynamics at the Arctic's land-sea interface. The BLE-LTER fills a need for strongly interdisciplinary and ecology-focused studies in the shallow coastal waters of the Arctic. Overarching goals are to improve our fundamental understanding of land-sea coupling and to project how climate change is altering coastal ecosystems.

BLE-LTER core program measurements include seasonal data collections for physical, biogeochemical, and biological properties in coastal lagoons across 500 km of coastline at three nodes distributed along the Alaskan Beaufort Sea coast at Utqiaġvik, Prudhoe Bay, and Kaktovik (Figure 2b). Two lagoons within each node are sampled during the periods of ice cover (April), sea ice breakup (June), and open water (August). In addition, the program collects continuous, high frequency measurements at multiple mooring sites at all three nodes. BLE-LTER inventory, process, and mooring observations are critical to understanding ecosystem responses to changes in sea ice extent and duration, coastal erosion, and freshwater inputs.

VESSEL-BASED MONITORING

Research programs from multiple Pacific Rim countries annually conduct research cruises across the Bering-Chukchi shelves and into the Arctic Basin. With some exceptions, research cruises north of Bering Strait are limited by sea ice to the months of July through October.

The Distributed Biological Observatory (DBO) is a change detection network that is evaluating alterations in the PAR in the context of declining seasonal sea ice, warming water temperatures, stratification changes, and other processes that are impacting all aspects of the overall ecosystem (Moore and Grebmeier, 2018). Initiated in 2010, the overarching goal of the DBO collaboration network is a comprehensive implementation of standardized ocean sampling as research cruises from the international community transit through the PAR. The surveys focus on regions of high productivity and biodiversity (five regions initially, later expanded to eight) that extend from the Northern Bering Sea to the Chukchi and Beaufort Seas (Figure 3a). Sampling includes seawater temperature, salinity, currents, nutrients, chlorophyll, carbon products, zooplankton, benthic fauna and sediments, and observations of seabirds (Kuletz et al., 2019) and marine mammals. The DBO is an international partnership involving Canada, China, Japan, Korea, Russia, and the United States, and many agencies within those countries, with collaborations for satellite observations, moorings, and autonomous sensor sampling in the DBO

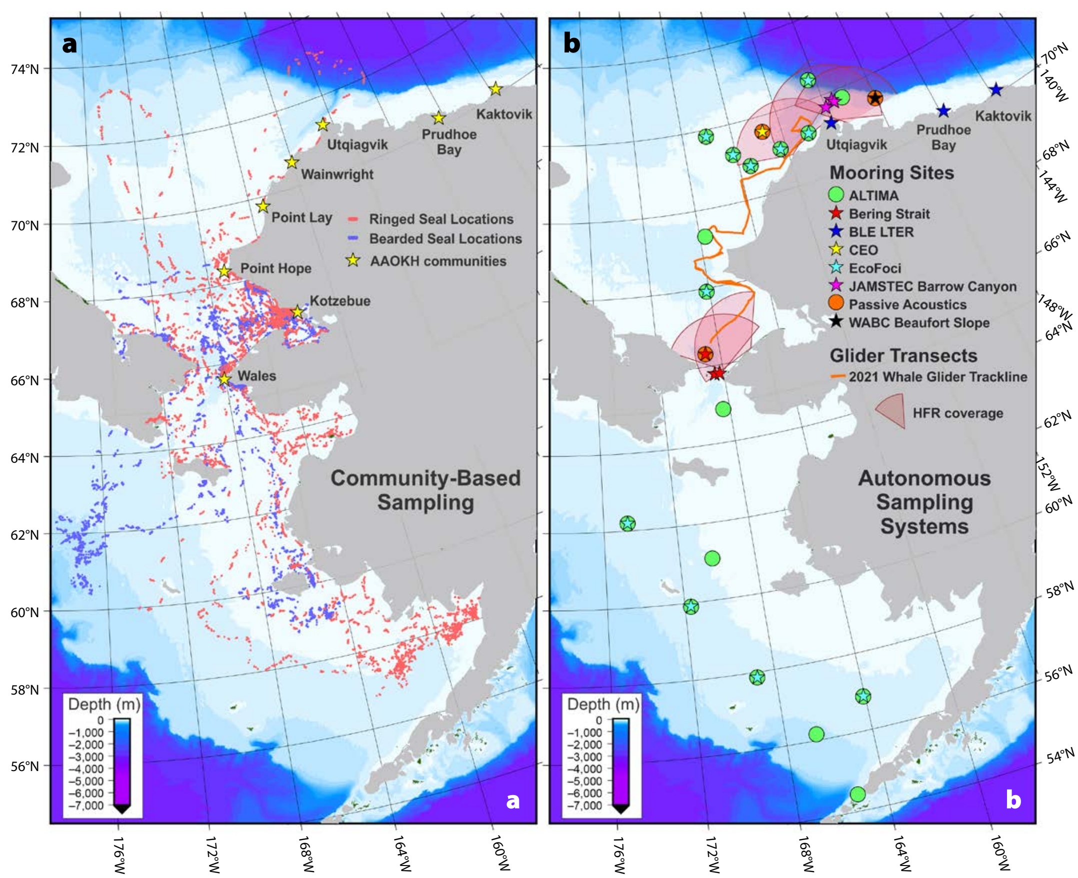


FIGURE 2. (a) Locations of current or past Alaska Arctic Observatory & Knowledge Hub (AAOKH) communities (yellow stars) and GPS locations of ringed (red) and bearded (blue) seals between September 2009 and July 2010. Seals were captured and tagged near Kotzebue during fall 2009 as part of a cooperative project between the Native Village of Kotzebue Environmental Program and the Alaska Department of Fish and Game. (b) Autonomous measurements: mooring sites (symbols), high frequency radar coverage (shaded arcs), and a 2021 passive acoustic glider track (orange line). Circles denote passive acoustic recorders, and stars denote multidisciplinary oceanographic moorings. Not shown: Saildrone tracklines that criss-cross the US Bering/Chukchi shelves.

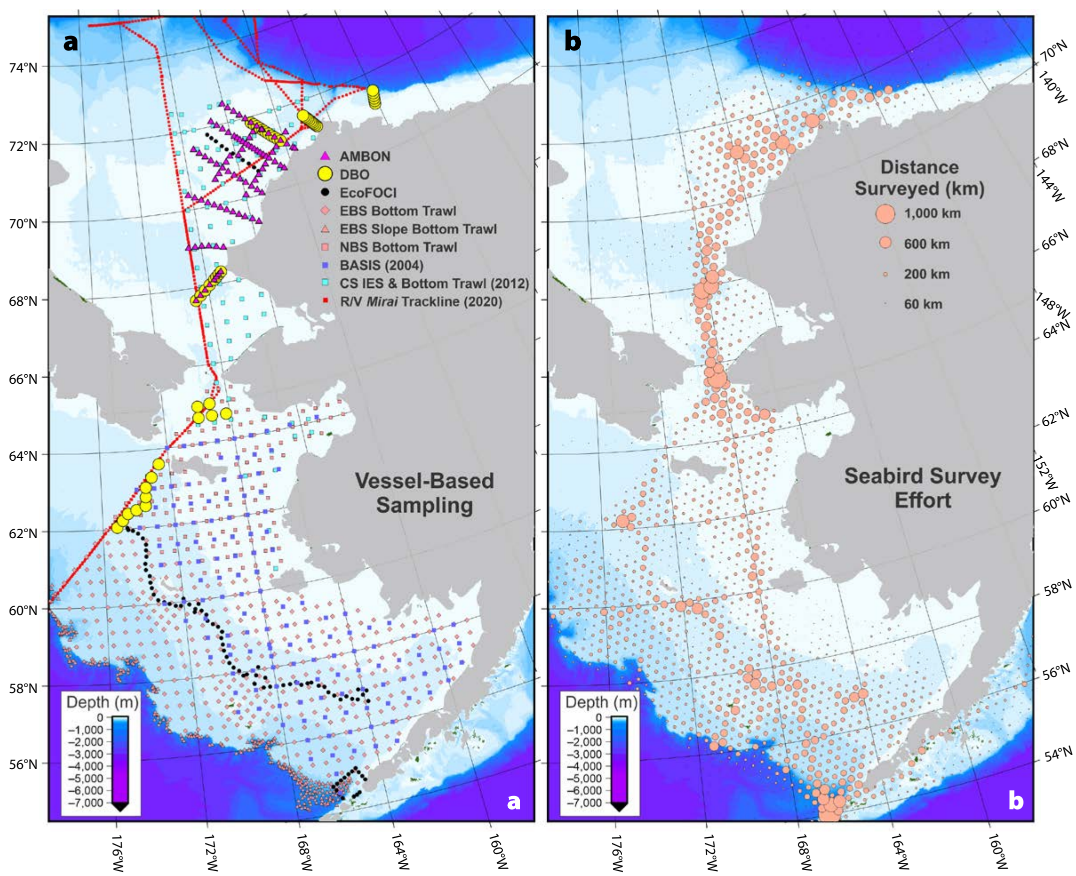
regions. Sampling is focused on transects centered on locations of high productivity, benthic biomass, and rates of biological change, using multiple international vessels annually. This DBO sampling concept is presently being expanded to other portions of the Arctic, including the Canadian Beaufort Sea, Baffin Bay, Davis Strait, waters near Svalbard, and possibly the Laptev Sea through German-Russian cooperative programs.

In the early 2000s, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) initiated studies to understand the oceanic halocline structures that help maintain sea ice distribution in the PAR. With decreasing sea ice in recent years, the research foci shifted to studying the physical oceanographic conditions associated with sea ice loss and associated impacts on marine biogeochemical cycles and ecosystems (e.g., Nishino et al., 2016). Resulting Arctic-focused projects since 2011 include the Arctic Climate Change Research Project under the Green Network of Excellence (GRENE; 2011–2016), Arctic Challenge for Sustainability project (ArCS; 2015–2019), and Arctic Challenge for Sustainability II project (ArCS II; 2020–2025). Although the GRENE project was mainly carried out by natural scientists, ArCS and ArCS II are more interdisciplinary, reflecting issues that also concern social scientists, decision-makers, practitioners, and the general public, particularly Indigenous residents of the Arctic coastal communities.

Observations of biological, chemical, and physical oceanographic conditions and ecological information on pelagic and benthic fish and invertebrate communities are provided by the NOAA Alaska Fisheries Science Center (AFSC), Bering Arctic-Subarctic Integrated Survey (BASIS; see station grid in Figure 3a). These surveys assist efforts to understand how the Bering Sea ecosystem is responding to loss of seasonal sea ice (Farley et al., 2020). Late-summer surveys occur in the southeastern Bering Sea biennially (even years) in late summer, and annually in the northern Bering Sea. In the Chukchi Sea, the Arctic Integrated Ecosystem Survey (IES) occurs less frequently (2003, 2007, 2012, 2013, 2017, 2019). Sampling at each station includes CTD profiles and discrete water samples for chlorophyll, nutrients, and environmental DNA (eDNA), net tows for zooplankton, and trawls for pelagic fishes, including young-of-the-year gadids, forage fishes, and juvenile salmonids. Benthic community ecology sampling in the Chukchi Sea began in 2017 and on BASIS surveys during 2018, targeting young-of-the-year fishes, crabs, clams and other invertebrates, and sediments.

The Groundfish Assessment (GAP) and Shellfish Assessment (SAP) Programs in the Resource Assessment and Conservation Engineering (RACE) division of the NOAA Alaska Fisheries Science Center (AFSC) have been conducting standardized bottom trawl surveys of groundfish and shellfish in the Bering Sea since 1982. The main goal of these bottom trawl surveys is to assess and monitor the conditions of these populations in the Bering Sea. The AFSC conducts four separate regional bottom trawl surveys: Eastern

FIGURE 3. (a) Vessel-based survey stations (symbols) and the 2020 R/V *Mirai* trackline as a representative effort in one recent year (red squares). (b) Vessel-based seabird survey effort (30 km grid cells) from 2006 to 2020 showing total kilometers of survey transect per grid cell.



Bering Sea shelf (EBS), EBS slope (EBSS), Northern Bering Sea (NBS), and Chukchi Sea (CS) surveys. Data collected are critical for managing fisheries, ecosystem monitoring, and advancing research on groundfish and crab populations throughout the region. Abundance, age and size composition data, and other biological and environmental oceanographic information from the bottom trawl surveys are used by AFSC, the North Pacific Fishery Management Council, and the Alaska Department of Fish and Game to manage groundfish and crab stocks. These data also build the basis for ecosystem models to improve scientific understanding of the Bering Sea ecosystem and to forecast potential changes to the ecosystem in response to the changing climate (Stevenson and Lauth, 2019).

In addition to population-level data, the AFSC bottom trawl surveys produce catch-per-unit-effort data on fish and invertebrate density that provide information on the distribution of marine fauna. These data have been critical in detecting and monitoring distribution shifts of groundfish in the region (Stevenson and Lauth, 2019). Survey efforts also include studies of genetics, diet, fish condition, acoustic backscatter, ecosystem indicators, and fish tagging. Oceanographic data routinely collected on the bottom trawl surveys include temperature, salinity, depth, and irradiance.

Seabirds are another upper trophic level indicator of marine ecosystem conditions. US Fish and Wildlife Service (USFWS) at-sea surveys (Figure 3b) describe temporal and spatial patterns and trends of marine birds in the PAR and examine changes in offshore seabird communities. The data are submitted to the North Pacific Pelagic Seabird Database for a variety of conservation, science, and management applications, and to inform environmental assessments of marine planning areas. They provide an upper trophic level component to multidisciplinary research and monitoring projects. Ultimately, the goals are to identify factors causing observed changes and to facilitate adaptive management for seabird populations. Ancillary observations of marine mammals are also recorded but are not used to estimate species' densities or abundance.

The seabird surveys depend on collaborations with vessel-based research programs (Table 1). By doing so, the USFWS has been able to leverage interagency and external grants to obtain greater survey coverage. Although project-specific data can provide valuable insights, combined data from multiple programs and years, often using repeated sampling stations (e.g., the DBO array; Kuletz et al., 2019), allow researchers to more fully examine seasonal and long-term patterns and changes in the seabird community. For example, Kuletz et al. (2020) found a northward shift in some seabird species and communities and declines in others during the exceptionally warm 2017–2019 period.

Complementary to the population assessment efforts, the Arctic Marine Biodiversity Observing Network (AMBON) contributes Arctic biodiversity data to the growing knowledge of Arctic systems across all trophic levels from microbes to whales (Iken et al., 2019). High biodiversity is thought to foster stable ecosystems because of the higher number, complexity, and redundancy of ecosystem functions that a larger number of coexisting species can support. Hence, contributing an Arctic perspective to national and international networks of Marine Biodiversity Observation (MBON) programs is a significant step forward in understanding global ocean processes and in managing, regulating, and mitigating human-ocean interactions. Vessel-based sampling occurs over several cross- and along-shelf environmental gradients from the southern to the northeastern Chukchi Sea or is conducted opportunistically in conjunction with other research efforts. Collections include microbes or eDNA from surface and bottom waters, small and large zooplankton from net collections, benthic macrofauna from grab samples, epibenthic invertebrates and demersal fishes from small beam trawls, pelagic fishes from midwater trawls, and shipboard observations of seabirds and marine mammals. Concurrently, water column and sediment environmental parameters are collected for relation to patterns in biodiversity. A goal of the AMBON project is to work collaboratively with other research efforts to optimize the production of new knowledge. For example, the AMBON project builds on prior studies in the Chukchi Sea and collaborates closely with the Chukchi Ecosystem Observatory (CEO) program, with the USFWS seabird at-sea surveys, and the DBO program.

AUTONOMOUS PLATFORM-BASED MONITORING

Autonomous sampling platforms (Figure 2b) can provide cost-effective means to monitor the marine realm using fixed installations and mobile autonomous uncrewed vehicles (AUVs, e.g., gliders and Saildrones). Moorings provide high temporal resolution data throughout the year, including the under-sampled fall, winter, and spring seasons when sea ice inhibits ship-based sampling and darkness precludes bird and mammal visual observations. Land-based high frequency radar (HFR) systems produce hourly maps of surface ocean currents that are used in oil spill responses, missing boater searches, and numerous scientific applications. While sensors that reliably measure the physical environment have been available for decades, recent advances in instrument technology now allow us to autonomously sample the marine ecosystem across many disciplines and including all trophic levels.

Since 1990, moorings in the Bering Strait (maintained by the University of Washington) have measured the key physical oceanic parameters of Pacific waters flowing towards the Arctic, quantifying velocity, temperature, salinity, and fluxes of volume, heat, and freshwater. Flow properties vary greatly both seasonally and interannually, driving the need for year-round measurements.

Since 2002, measurements have also been made of ice velocity and thickness, and since 2007, there have been separate measurements of upper layer temperature and salinity. The Diomede Islands split Bering Strait into two channels—one in the United States and one in Russia. Originally, moorings were placed in both channels and at a site 35 km north of the strait proper, a location found to give a useful average of the flow properties through both channels. The mooring placements (Figure 2b) allow quantification of the flow even when access to the Russian channel is not possible. The full time series shows increasing northward flow (~70% increase since 2001), warming (~0.1°C yr^{-1} in summer), longer open water duration (~1.5 days per year), and dramatic freshening, especially in winter (~0.03 psu yr^{-1}; Woodgate, 2018; Woodgate and Peralta-Ferriz, 2021). These data represent one example of long-term monitoring that revealed signals not anticipated at the program onset; documentation of these changes is now foundational to our understanding of PAR changes across physical, chemical, and biological systems.

JAMSTEC has maintained subsurface oceanographic moorings at the mouth of Barrow Canyon in the Northeast Chukchi Sea since 2000, monitoring the volume, freshwater, and heat transport of Pacific-origin water into the Arctic Basin. Barrow Canyon, a major conduit for this flow, is also where deeper Atlantic-origin water sometimes upwells onto the Chukchi shelf. The moorings assess winter water fluxes, which strongly influence the Arctic Basin environment by ventilating the interior halocline and providing nutrients that spur primary production, while summer water is a predominant source of heat and freshwater (e.g., Itoh et al., 2013). Annual mean volume transport through Barrow Canyon (0.45 Sv) represents 55% of the long-term mean Pacific Water inflow through Bering Strait (Itoh et al., 2013) and ~94% of the Bering Strait transport during summer. Over the last decade, warm Pacific summer water has significantly contributed to both sea ice melt in summer and a decrease in sea ice formation during winter.

As part of the US National Science Foundation-supported Arctic Observing Network, the Woods Hole Oceanographic Institution has maintained a year-round mooring on the Beaufort continental slope in the western Arctic boundary current (WABC), along with biennial autumn ocean current shipboard surveys. The WABC, a critical conduit of Pacific water, advects elevated concentrations of nutrients, chlorophyll, dissolved and particulate organic carbon, and zooplankton towards the Canadian Arctic Archipelago (Pickart et al., 2013). Bowhead and beluga whales congregate near the current along the outer shelf and continental slope of the Beaufort Sea (Stafford et al. 2021). Due to wind-driven upwelling/downwelling and hydrodynamic instability, the WABC fluxes a substantial fraction of its mass, heat, freshwater, and biogenic content offshore, impacting the Arctic interior water column, ice concentration, and ecosystem. The mooring provides time series of physical and biogeochemical properties at a location that is critical for understanding the fate of Pacific water in the Arctic and its impacts. Measurements of mass, heat, and freshwater fluxes, as well as transport of biogenic material and upwelling and downwelling events are also documented and quantified from the mooring data. This allows for identification of causal relationships between the physical environment and the ecosystem, ranging from nutrient dynamics to higher trophic levels.

As one node in a greater network of moored observatories that monitor Alaska's large marine ecosystems, the University of Alaska Fairbanks (UAF) Chukchi Ecosystem Observatory (CEO) program maintains a cluster of highly instrumented subsurface moorings on the Northeast Chukchi continental shelf (Hauri et al., 2018). Electronic, optical, and acoustic data loggers record measurements that characterize the physical environment (temperature, salinity, pressure, currents, waves, ice draft, irradiance, optical backscatter), the chemical environment (NO_3, colored dissolved organic matter, dissolved oxygen, pH, pCO_2), phytoplankton standing stock (chlorophyll *a* fluorescence), zooplankton and fish densities (acoustic backscatter), and marine mammal presence (underwater sound). An autonomous time-series sampler collects discrete water samples for subsequent laboratory analyses of eDNA and inorganic nutrients (NO_3, NO_2, NH_4, SiO_3, PO_4); time-series sediment traps collect zooplankton and meroplankton, along with sinking particulate matter for quantification of fluxes of phytoplankton species, total particulate matter (TPM), particulate organic carbon (POC), and zooplankton fecal pellets (Lalande et al., 2021). A time lapse camera system planned for deployment in 2022 will capture a photographic history of the seafloor, fishes, and epifauna. These co-located observations thereby provide views into the year-round functioning of the Chukchi shelf ecosystem across all trophic levels and spanning the benthic, pelagic, and sympagic (ice) realms.

By deploying passive acoustic sensors on gliders and oceanographic moorings instrumented with other sensors, the relationship between top trophic level marine mammal occurrence and their environment can be elucidated (Stafford et al., 2021). The University of Washington has deployed acoustic sensors quasi-continuously year-round on oceanographic moorings since 2008 in the Bering Strait, Beaufort Sea, and Northern Chukchi Sea; since 2016 at the Chukchi Ecosystem Observatory; and since 2013 on gliders deployed from the Bering Strait moorings cruise for annual transits of the Chukchi shelf from Bering Strait to Barrow Canyon (Baumgartner et al., 2014). The AFSC Marine Mammal Laboratory has maintained approximately 20 subsurface passive acoustic recorder moorings that extend from the Aleutian Islands to the central Beaufort Sea and the Northern Chukchi Sea as part of the Arctic Long-Term Integrated Mooring

Array (ALTIMA). ALTIMA moorings have been deployed annually for over a decade, with most co-located with biophysical instrumentation (see EcoFOCI below) and at the five original DBO sites.

For both passive acoustic programs, acoustic presence is determined for Arctic and subarctic marine mammal species including baleen whales, odontocetes, and pinnipeds. Because these species represent a wide variety of feeding guilds, from specialists to generalists, from planktivores to piscivores, and from obligate to facultative benthic feeders, these data are ideal for examining the consequences of change in many different bottom-up processes. Passive acoustic data have provided novel information on the migratory timing and presence of Arctic and subarctic species. For instance, bowhead and beluga whales have recently delayed their fall migrations out of the high Arctic (Hauser et al., 2017; Stafford et al., 2021), subarctic fin and killer whales are moving north and spending more time in an ice-free Chukchi Sea (Stafford, 2019; Escajeda et al., 2020), and critically endangered North Pacific right whales are being detected further north in the Bering Sea (Wright et al., 2019). The data provide baseline noise levels for evaluating acoustic environment changes caused by increased industrial and vessel traffic presence and climate change-induced extension of the open-water season (Wright et al., 2018).

NOAA's Ecosystems and Fisheries-Oceanography Coordinated Investigations (EcoFOCI) program assesses the ecosystems of the North Pacific Ocean, the Bering Sea, and the US Arctic to improve understanding of ecosystem dynamics and apply that understanding to the management of living marine resources (Tabisola et al., 2021). EcoFOCI scientists integrate field, laboratory, and modeling studies to determine how variability in biological and physical factors, including climate, influence Alaska's large marine ecosystems. Long-term moored observatories are maintained at five sites in the Bering Sea (Figure 2b) and seven sites in the Chukchi Sea. These measurements usually include ice draft, currents, temperature, salinity, chlorophyll fluorescence, oxygen, nitrate, and passive acoustics to detect marine mammals. Select sites also include sediment traps that collect sinking organic and inorganic particles; water samplers for isotopes, nutrients, eDNA, and phytoplankton speciation; and instruments that measure pCO_2, colored dissolved organic matter, primary production via oxygen, and gas ratios. Technological advances are improving our ability to observe the Arctic. For instance, new moorings have a surface component that is programmed to sink with sea ice arrival. During the following spring, instruments detect sea ice retreat, and at the appropriate time, the surface component re-floats and resumes sampling. Other innovations include low-cost air-deployed coastal profiling floats, under-ice pop-up floats, in situ microbial incubation systems, and imaging systems with artificial intelligence to estimate, identify, and determine the abundance of phytoplankton, zooplankton, and fish.

EcoFOCI moored observations are closely linked to annual research cruises that assess the rapidly changing Bering Sea and the US Arctic. Three of the moorings are located in DBO regions, while others are associated with long-term NOAA cruise transects and seabird sampling, including the Bering Sea 70 m isobath transect and transects across Unimak Pass and at Icy Cape. Sampling on these transects includes CTDs; collection of discrete water samples for chlorophyll, nutrients, oxygen and eDNA; and zooplankton nets; visual observations detect marine mammals and birds. The hydrographic transects are conducted once or twice a year, and data from the moorings place them within a longer temporal context. The data validate and inform regional ecosystem models and play an important role in understanding ecosystem dynamics, especially in the context of climate and ocean changes (Hunt et al., 2011; Stabeno and Bell, 2019; Stabeno et al., 2020).

FINAL REMARKS

The efforts represented by this collection of collaborative long-term monitoring programs enable a biologically focused scientific foundation for understanding how the Alaskan Arctic marine ecosystem is changing as water temperatures warm and sea ice declines. We expect these data will continually improve the ability of resource management and US mission-oriented agencies (e.g., NOAA, Bureau of Ocean Energy Management) to refine actions that impact marine resources, local communities, and biological systems.

Although organizationally separate, there exist many formal and informal linkages between the programs described herein. Oceanographic moorings carry passive acoustic recorders, seabird observers join at-sea surveys, and social media postings from community-based programs document local observations that inform research scientists. Biogeochemical time-series data from field studies help constrain and validate the functioning of Earth system models. Such partnerships encourage cross-program, interdisciplinary collaborations that help scientists leverage the monitoring data into applications to emerging issues and analyses that were not necessarily identified at the start of each monitoring program. For example, mooring, shipboard hydrography, plankton net, fisheries trawl, and seabird data together helped Sigler et al. (2011) refine our understanding of PAR biogeographical provinces and their relations to the physical environment.

In addition to the extensive efforts described here, numerous additional ongoing long-term monitoring programs include, but are not limited to: study of black guillemots at Cooper Island (Divoky et al., 2021); benthic studies of the Stefansson Sound Boulder Patch kelp community (Wilce and Dunton, 2014); monitoring of seabird mortality by the Coastal Observation and Seabird Survey Team (COASST; Parrish et al., 2017); USFWS Alaska Maritime National

Wildlife Refuge seabird colony monitoring; US Geological Survey polar bear surveys; State of Alaska Norton Sound bottom trawl surveys (Hamazaki et al., 2005) and ice seal data sets (Crawford et al., 2015); assessments of harmful algal blooms (with some undertaken as part of the DBO effort; Anderson et al., 2021); community-based monitoring of coastal erosion; aerial surveys of marine mammal populations; NOAA's Ocean Noise Reference Station Network; Korean surveys on the icebreaker R/V *Araon*; Chinese observations from the icebreaking R/V *Xue Long*; Russian fishery surveys in the Russian Federation exclusive economic zone; the North Slope Borough Division of Wildlife Management bowhead whale survey and other studies; investigations of bowhead whale prey (Ashjian et al., 2021); studies conducted by Kawerak and other regional non-profit corporations; and efforts organized by environmental coordinators in most coastal villages. The Local Environmental Observer (LEO) program is a citizen observation network with participants distributed throughout Alaska (Brubaker et al., 2013), as is the Indigenous Sentinels Network (Divine and Robson, 2020). Satellite-based sensors provide additional monitoring context with decades of ice cover and ocean color measurements (e.g., Frey et al., 2015).

All of the projects listed above and in **Table 1** deal with the inevitable challenges and uncertainties in funding availability, the vagaries of weather and sea ice, and the surprises that arise while doing Arctic fieldwork. This paper serves as a testament to the perseverance needed to accomplish reliable observations over extended periods of time, to the societal importance ascribed to maintaining such efforts, and to the benefits of inter-program collaborations. Over time, the value of long-term monitoring data only increases as new questions emerge that can be assessed with the benefit of existing monitoring data, and especially when new data applications arise through synergy of independently operating efforts.

SUPPLEMENTARY MATERIALS

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EMERGING TECHNOLOGIES AND APPROACHES FOR IN SITU, AUTONOMOUS **OBSERVING IN THE ARCTIC**

By Craig M. Lee, Michael DeGrandpre, John Guthrie, Victoria Hill, Ron Kwok, James Morison, Christopher J. Cox, Hanumant Singh, Timothy P. Stanton, and Jeremy Wilkinson

ABSTRACT. Understanding and predicting Arctic change and its impacts on global climate requires broad, sustained observations of the atmosphere-ice-ocean system, yet technological and logistical challenges severely restrict the temporal and spatial scope of observing efforts. Satellite remote sensing provides unprecedented, pan-Arctic measurements of the surface, but complementary in situ observations are required to complete the picture. Over the past few decades, a diverse range of autonomous platforms have been developed to make broad, sustained observations of the ice-free ocean, often with near-real-time data delivery. Though these technologies are well suited to the difficult environmental conditions and remote logistics that complicate Arctic observing, they face a suite of additional challenges, such as limited access to satellite services that make geolocation and communication possible. This paper reviews new platform and sensor developments, adaptations of mature technologies, and approaches for their use, placed within the framework of Arctic Ocean observing needs.

INTRODUCTION

Environmental change occurs in the Arctic at a greatly accelerated rate, warming at twice the global average, with profound impacts on the marine sector. Most apparent is the rapid decline in summertime sea ice extent, which in recent years has been roughly half of what it was in the late 1970s (Stroeve and Notz, 2018; Meier and Stroeve, 2022, in this issue). This loss has been accompanied by a shift to a younger, thinner, more mobile pack (Lindsay and Schweiger, 2015; Kwok, 2018) and a lengthening of the open water season (Stroeve et al., 2014). These changes lead to shifts in the dynamics that govern atmosphere-ice-ocean interactions, with broad impacts that include changes in weather, circulation, ecosystems, and biogeochemistry.

The magnitude and speed of Arctic environmental changes pose significant societal challenges. Climate-related hazards include accelerated coastal erosion brought about by more energetic surface waves. Food security is threatened by ecosystem shifts and unreliable ice conditions that complicate subsistence hunting. Arctic communities are finding it difficult to adapt to rapid changes in the ecosystem services they rely upon. Moreover, these hazards are not confined to the Arctic, as Arctic change may contribute to severe weather patterns in the mid-latitudes (e.g., Francis and Vavrus, 2012). As sea ice decline offers new opportunities for shipping, fisheries, resource extraction, and tourism, increased human activity brings new risks that demand expansion of capabilities such as search and rescue and oil spill response.

Observations provide a foundation for understanding and predicting Arctic change, but the challenges associated with operating in this remote, difficult environment have made the region data sparse. Recent results based on satellite altimetry (see Morison et al., 2022, in this issue) illustrate the difficulties imposed by the sparsity of in situ measurements. Ice cover impedes access to much of the Arctic, biasing existing measurements toward summer when sea ice extent is at a minimum, and complicating the task of achieving broad, distributed geographic coverage. Instruments deployed on sea ice are constrained by the circulation patterns of the ice itself. Autonomous instruments operating beneath the ice cannot access GPS and satellite communications that modern oceanographic systems, such as the Argo float array (Riser et al., 2018), rely on for geolocation and data transmission. The dynamic nature of sea ice complicates collection of collocated measurements across ocean, ice, and atmosphere. Added to this are issues such as severe cold, high winds, icing, and polar bear attacks on equipment that limit development of untended ice-based systems capable of collecting sustained, year-round atmospheric measurements. These challenges often demand development of larger, more complex instruments, while sustained, distributed observing efforts call for systems that are lighter and less costly (as defined by the sum of hardware, operations, and logistics).

Arctic Ocean observing serves a broad range of stakeholder needs that in turn place strong requirements on spatial and temporal scope and scales, and on data delivery. These can be organized into three overlapping domains, each with distinct demands for observations that guide the choice of platforms and approaches (e.g., Lee et al., 2019): (1) long-range planning and policy, (2) strategy, and (3) tactics. **Policy** (Figure 1, green) involves use of data to understand environmental change and make long-range predictions that inform decisions regarding management of natural and built environments on decadal timescales. This need often dictates distributed measurements of large geographic scope, sustained over decades. Real-time data delivery is not important, but maintenance of long, consistent records is critical. **Strategy** (Figure 1, orange) involves use of environmental data to support activity at timescales of seasons to years. Observations focus regionally and might support modeling efforts that require regular, near-real-time delivery of distributed observations. **Tactics** (Figure 1, purple) is the domain of situational awareness and operational forecasting to support day-to-day activity, such as search and rescue, subsistence hunting, vessel routing, and toxic algal bloom detection. Measurements might be confined near areas of human activity, with a premium on rapid delivery of data and analysis products. Engagement of coastal communities in the conceptualization, planning, and implementation of observing activities can improve relevance and, given appropriate choices of technologies, might offer efficient, sustainable paths for operations.

Ship-based surveys, camps established on the sea ice, and moored instruments have historically been responsible for most data collection in the Arctic Ocean. Ships and ice camps provide extensive in situ sampling capabilities and collect intricate measurements that are challenging or impossible to accomplish using the current generation of remote sensors. Moorings provide time series in locations such as shallow shelves and strong boundary currents that can be challenging for other platforms, and they can host large, power-hungry sensors that smaller platforms cannot accommodate. Moreover, ships remain critical for the deployment of moorings and small autonomous platforms. While ships and moorings will remain critical to Arctic observing, this paper focuses on exploring the capabilities provided by smaller autonomous platforms, including ice-tethered buoys, floats, autonomous underwater vehicles and gliders, and the sensors they support.

Emerging technologies, applications of existing technologies, and novel approaches for employing them offer paths for expanding Arctic Ocean observing to meet societal needs (Figure 2). Satellites provide long-term, pan-Arctic

FACING PAGE. R/V *Sikuliaq* transiting through first year sea ice to deploy instruments for the Office of Naval Research Arctic Mobile Observing System program, October 2021.

measurements of an expanding range of surface properties. New developments and ice-capable adaptations of autonomous platforms, including lightweight drifters, floats, and gliders as well as larger, more capable underwater, surface, and airborne vehicles, offer expanded geographic reach and persistence. Novel bio-optical, acoustic, image-based, and biogeochemical sensors, deployed on a range of ice-based, moored, and drifting platforms, promise to deliver key biological and chemical measurements at scales similar to those of physical properties. Advances in acoustic infrastructure provide new strategies for geolocation and data transmission for platforms operating beneath the ice. Used together, these systems can characterize spatial and temporal scales that have previously been difficult to achieve.

This paper focuses on autonomous platforms applied primarily to the deep, interior basins of the Arctic Ocean, and provides examples of emerging technologies, adaptations of mature technologies to the Arctic environment, and approaches for using heterogeneous systems of platforms to address challenges in Arctic Ocean observing. While many of these technologies can be readily used for collecting measurements across critical Arctic shelf systems, these shallow, ice-threatened environments pose unique, highly demanding challenges. Danielson et al. (2022, in this issue) provide an example of a collaborative Arctic shelf observing system that employs a diverse range of technologies and approaches, including some of the autonomous platforms discussed here. Recent insights enabled by satellite remote sensing reveal shortfalls in existing in situ observing capabilities (see Morison et al., 2022, in this issue). Here, this motivates a review of selected technologies for in situ observing that highlights challenges and promising new developments, followed by a discussion of emerging directions in sensor development. The paper concludes with recommendations stemming from ongoing development efforts.

AUTONOMOUS PLATFORMS FOR IN SITU ARCTIC OCEAN OBSERVING

The spectrum of Arctic Ocean observing systems (Figure 2) provides a framework for considering a range of mature and emerging technologies for autonomous in situ observing. The following discussion presents an overview of the state of the art of key platform classes, drawing on examples of emerging technologies to illustrate instrument capabilities and challenges.

Distributed Observations from Ice-Tethered Platforms

Ice-tethered systems have long been the backbone of autonomous seasonal and interannual observations of physical structure of the upper Arctic Ocean. Instruments such as Ice-Tethered Profilers (ITP; Figure 2a; Krishfield et al., 2008), the Autonomous Ocean Flux Buoy (AOFB; Figure 3a, Stanton et al., 2012), and Ice Mass Balance Buoys (IMB; Richter-Menge et al., 2006; Perovich, 2022, in this issue) routinely sample for periods of months to years while suspended from drifting sea ice, geolocating and transmitting data in real time using satellite services. Increasingly, changes in seasonal ice cover have made it more difficult to find large, stable ice floes that maximize instrument lifetimes, motivating efforts to harden systems to improve survivability during melt out and freeze-up, and to make open-water deployments possible. Drifting instruments, both on the ice and within the water column, can be highly effective for process investigations, but challenging to use for sustained, regionally focused

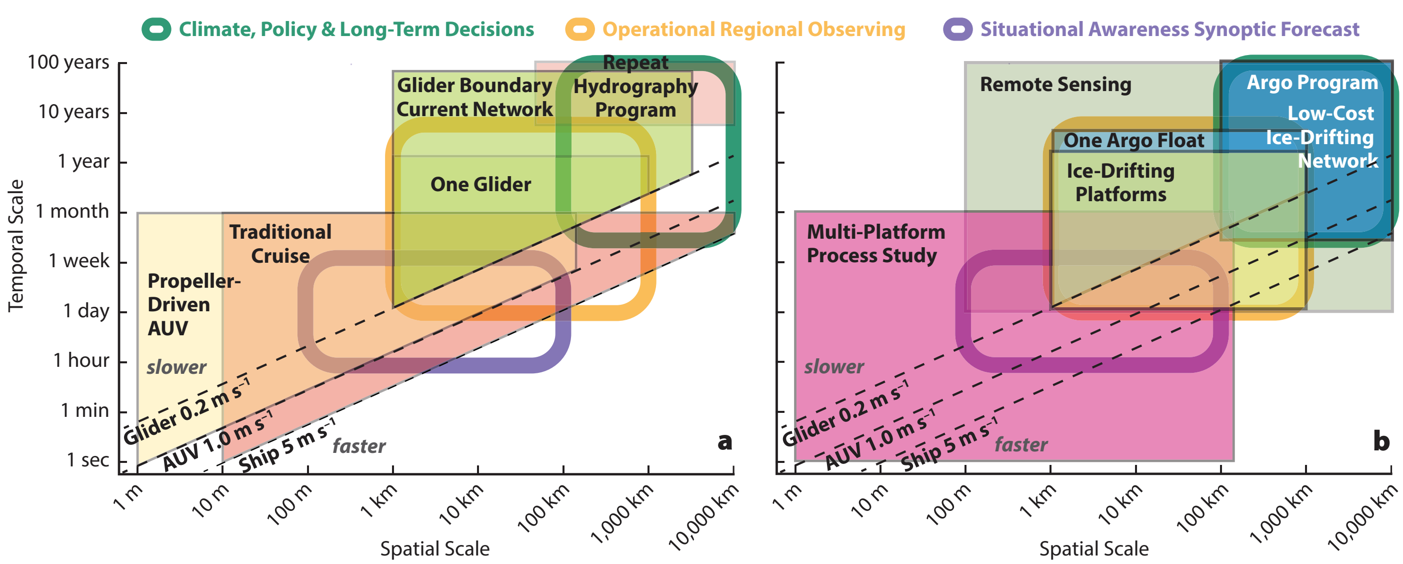

FIGURE 1. Spatial and temporal coverage provided by (a) mobile and (b) drifting platforms. Thick boxes mark the requirements of three notional observing systems. Lightly shaded areas denote scales sampled by selected platforms or networks of platforms, with the magenta box denoting the potential scope of a typical multi-platform process study. With the exception of remote sensing, all platforms shown provide vertical sampling though the water column. Maximum depth and ability to sample near the ice-ocean or atmosphere-ocean interface vary by platform.

observing networks in energetic environments, where ice drift and currents can rapidly carry instruments away from the region of interest. The combined cost of hardware and deployment logistics can make large-scale deployments impractical, limiting the utility of ice-tethered systems for broad, distributed observing. These challenges aside, ice-tethered platforms complement capabilities provided by other approaches and remain a critical tool for in situ observing at all scales. The Dynamic Ocean Topography (DOT) buoy, Warming and iRradiance Measurements (WARM) buoys, and Atmospheric Surface Flux Stations (ASFSs), each described below, provide examples of emerging developments that extend the utility of these established technologies into other applications.

Dynamic Ocean Topography Buoy

The DOT buoy (**Figure 3b**) was developed to make precise measurements of sea surface height (SSH) and precipitable water vapor (PWV), aimed at providing the long-duration, in situ measurements needed to validate remotely sensed estimates of SSH, such as the NASA ICESat-2 and Surface Water and Ocean Topography (SWOT) altimeter missions (see Morison, et al., 2022, in this issue). Dynamic ocean topography, derived from SSH, constitutes the surface pressure gradient that drives geostrophic surface velocity, V_{geo}. DOT observations combined with density profiles measured by Argo floats or ITPs to infer velocity shear allow estimation of absolute water velocity versus depth. In ice-covered seas, except during high winds, the sea ice drift, V_{ice}, largely follows V_{geo} (Kwok et al., 2013). The difference between V_{ice} and V_{geo} plays a critical role in stabilizing the doming of the Beaufort Sea Gyre (Dewey et al., 2018). Furthermore, cross-shelf gradients in DOT drive secondary circulations, upwelling, and downwelling, and are responsible for shelf-basin exchanges that are critical to maintaining the Arctic Ocean's cold halocline (Morison et al., 2012).

The DOT buoy provides full GPS data to allow Precise Point Positioning determination of SSH with centimeter-scale accuracy. The resulting in situ SSH data are suitable for validation of ICESat-2 observations over long periods of time. The buoy resolves major tidal constituents as well as other high-frequency SSH variability unresolvable from remote sensing. A dual frequency GPS also allows the calculation of integrated PWV based on the wet zenith delay. A pressure

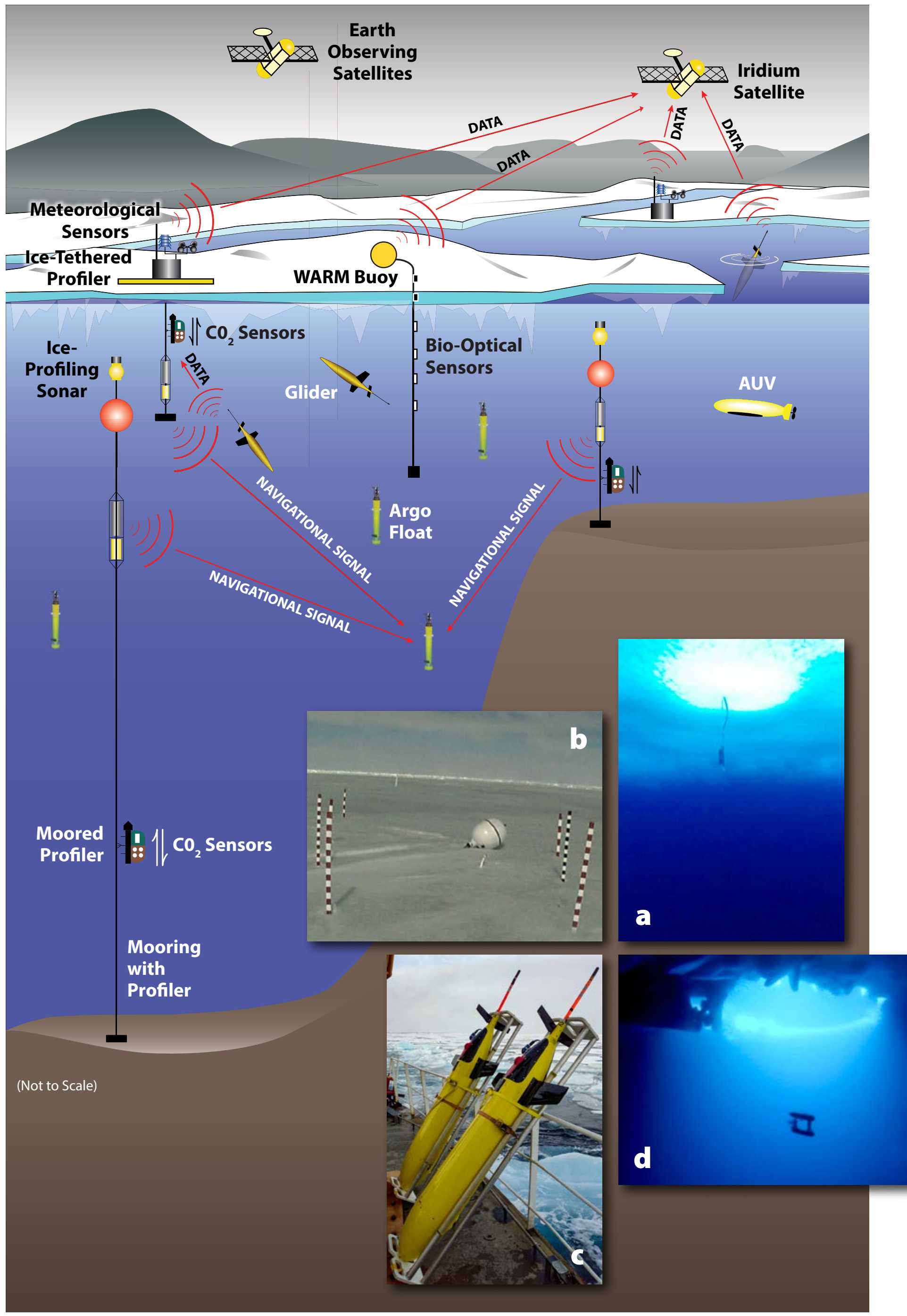

FIGURE 2. Technologies for autonomous Arctic Ocean observing. Red lines mark examples of underwater acoustic navigation and communication paths and satellite telemetry for instruments on the surface. (a) Sensors for measuring pCO_2 and O_2 deployed in the Beaufort Gyre on an Ice-Tethered Profiler. (b) A buoy designed for Warming and iRradiance Measurements (WARM). (c) Gliders ready for launch into the central Beaufort Sea. (d) The Jaguar autonomous underwater vehicle (AUV) deployed through an open lead for sea ice characterization.

sensor measures the freeboard of the GPS antenna phase center, a barometer measures atmospheric pressure to allow correction for the inverse barometer effect, and air temperature is measured for use in the determination of PWV. Standard meteorological measurements further augment the existing International Arctic Buoy Program (IABP) array in the Arctic Ocean. Data are telemetered through an Iridium link.

One DOT buoy was installed in Elson Lagoon, Alaska, in spring 2019 for comparison with an ICESat-2 target-of-opportunity. It was redeployed in the Beaufort Gyre in September 2019. A second buoy was deployed in the Eurasian Basin in October 2019 as part of the Multidisciplinary drifting Observatory for the Study of Arctic Climate program (MOSAiC; Shupe and Rex, 2022, in this issue). Both buoys survived for seven months. ICESat-2 photon heights from the target-of-opportunity pass on April 18, 2019, were within 0.003 m of the buoy-measured surface heights at the time of the pass and 0.02 m below the one-hour average of buoy-measured height, indicating the inherent accuracy of the buoy and ICESat-2 is at the 2 cm level. A third DOT buoy was deployed in spring 2022 in the Beaufort Sea by the Navy Ice Exercise (ICEX 2022) and is still reporting as of this writing.

Biogeochemical Measurements from Buoys

Integration of biological sensors onto ice-tethered platforms has enabled autonomous investigations of biogeochemical processes. Drifting with multiyear ice, ice-tethered systems equipped with sensors for light, chlorophyll and dissolved organic matter fluorescence, and backscatter at 700 nm have provided detailed vertical profiles several times a day. These data reveal differences in the vertical extent of algae biomass driven by euphotic depth across Beaufort and Central basins. Large aggregates of particles, assumed to be biological in nature, were observed sinking out of the euphotic zone, providing insight into sequestration of carbon in the central Arctic (Laney et al., 2014, 2017).

The WARM buoy (**Figure 2b**) was designed as a cost-effective ice-tethered platform to collect bio-optical observations throughout the melting phase of seasonal ice on the Arctic shelves. WARM buoy instruments include light, chlorophyll and dissolved organic matter fluorescence, backscatter at 532 nm, temperature, and salinity (Hill et al., 2018, 2020). In comparison to previous bio-optical systems, the sensors are static, swapping vertical resolution for the ability to collect measurements within the ice, at the ice-water interface, and within several meters of the bottom of the ice. Frequency of observations can be high and is limited only by battery life and satellite uplink. WARM buoys have observed under-ice phytoplankton blooms as well as intense and long-lived ice algal blooms in the Chukchi Sea (Hill et al., 2018).

Another novel technology for collecting observations close to the underside of the ice is the pop-up buoy, which is initially tethered to a bottom mooring and then released in the spring to nestle at the base of the ice and collect temperature, light, and chlorophyll fluorescence. These

FIGURE 3. (a) Autonomous Ocean Flux Buoy (AOFB) being deployed at part of the 2018 Office of Naval Research (ONR) Stratified Ocean Dynamics of the Arctic Ocean (SODA) program. (b) Deployment of a Dynamic Ocean Topography (DOT) buoy from USCGS *Healy* in 2018. (c) Ice Gateway Buoy equipped with meteorological sensors drifting in the central Beaufort Sea during the 2021 ONR Arctic Mobile Observing System (AMOS) program. (d) Deployment of an acoustic navigation source.

buoys record their data and then transmit via satellite uplink once the ice above them melts. Pop-up buoys deployed with Chukchi shelf moorings have observed dense, under-ice blooms in May on the ice-covered shelf (Stabeno et al., 2020). All of these systems have provided critical observations of conditions within and underneath the ice cover, observations that are critical to our ability to predict climate-related changes in Arctic primary productivity.

Mobile Platforms Operating Under the Ice

Small, long-endurance, mobile autonomous platforms, including profiling floats, surface drifters, autonomous surface vehicles, and buoyancy-driven gliders have expanded open-ocean observing to cover spatial and temporal scales that were previously difficult or impossible to resolve, but they have seen limited use in the Arctic. Relatively low hardware cost and light weight, flexible logistics make these platforms highly scalable and thus well suited for a wide range of observing tasks. Shallow water and challenging bathymetry complicate operation of gliders and profiling floats in the ice-covered nearshore, where long-range acoustic navigation is difficult to accomplish. The challenge of achieving year-round, real-time data return from instruments operating beneath the sea ice limits their utility in observing systems focused on serving tactical needs (**Figure 1**). Recent advances in profiling floats, long-endurance gliders, and the acoustic infrastructure that facilitates their operation in ice-covered environments will enable broader application of these platforms.

Profiling Floats

Profiling floats, which have revolutionized global ocean observing through the Argo program (Roemmich et al., 2009), offer a promising path for achieving sustained, distributed observations across the Arctic Ocean. Argo relies on low per-unit cost (~$25k for CTD-only units) and flexible logistics to maintain an operational network of nearly 4,000 floats that provide profiles at 300 km/10-day resolution across the ice-free oceans. Argo floats are a mature technology, mass-produced by several manufacturers, and have well-quantified reliability statistics. Because these floats can be deployed from vessels of opportunity or dropped from aircraft by personnel with little specialized training, the Arctic community's long-standing culture of collaboration could provide many opportunistic deployments from research and commercial vessels, and aircraft-based deployments through operations such as the US Coast Guard's routine reconnaissance flights.

Instruments operating beneath the ice cannot access satellites to geolocate and communicate, and must instead rely on alternative solutions, such as acoustics, or operate without. Previous efforts have successfully demonstrated under-ice acoustic navigation for extended (weeks to months) glider missions (e.g., Webster et al., 2014), which could be readily transferred to floats. Existing technologies for high bandwidth acoustic communications have ranges of only kilometers, but dramatic reductions in summertime sea ice extent offer large areas of seasonal open water, raising the possibility that floats could transfer data via satellite during the summer months. Within the framework of a coupled ocean-sea ice state estimate, Nguyen et al. (2020) find that even when floats are allowed geolocation and data transfer only when operating in low ice concentrations or in open water, the resulting data could still be useful for constraining numerical models and reducing hydrographic uncertainties.

Pilot efforts have achieved successful profiling float deployments in polar regions. As part of NOAA's Arctic Heat experiment, Air-Launched Autonomous Micro Observer (ALAMO) profiling floats (Jayne and Bogue, 2017) deployed in late summer 2016 successfully sampled through the winter, and resurfaced in open water in spring 2017, though data transfer was limited due to the choice of a short surface interval (Wood et al., 2018). Development of acoustic geolocation and ice avoidance for floats operating in the Antarctic (Klatt et al., 2007) demonstrates successful implementation of these technologies on profiling floats and provides guidance for efforts to move these capabilities into the Arctic.

Long-Endurance Gliders

Buoyancy-driven gliders (**Figure 2c**; Lee and Rudnick, 2018) complement the sampling capabilities of profiling floats, resolving scales of kilometers and hours, while offering persistent sampling over seasons to years (**Figure 1**). Per-profile costs are similar to those of floats, but glider profiles are finely spaced along transit lines rather than distributed over broad regions. This makes gliders well suited for sustained sampling of regions with strong lateral contrasts, such as boundary currents, fronts, and eddies, and for capturing episodic processes that unfold at small scales. Long-endurance gliders are a mature technology with a record of scientific achievements (Rudnick, 2016), but they have the same geolocation and communication challenges as profiling floats when operating in ice-covered regions.

Multi-month missions under ice require extending the existing capabilities of gliders. Unlike floats, gliders actively navigate between commanded waypoints and thus require real-time geolocation. Implementation of long-range, low-frequency (1 kHz) acoustic navigation, starting with the system originally used for Ranging and Fixing of Sound (RAFOS) floats (Rossby et al., 1986) and onboard multilateration algorithms fulfilled this need for vehicles working in polar regions. Existing underwater gliders communicate to shore multiple times each day, and in some sense could be considered high-latency remote control vehicles. Seagliders operating in polar regions might go for many months without human intervention and thus require approaches and programming that provide extended autonomy, including navigation, mission decision-making, onboard troubleshooting, and ice avoidance. Though an inadequate substitute for satellite communications, high frequency (~10 kHz) acoustic communications provide limited through-water data transfer at ranges of a few kilometers.

Long-endurance Seagliders, geolocating from low frequency (~1 kHz) acoustic sources, have been used for multi-month missions under sea ice in the Arctic and Antarctic. Initial efforts focused on achieving year-round occupation of a section across the seasonally ice-covered Davis Strait (Curry et al., 2014; Webster et al., 2014). The limited 300 km-wide domain, Greenland-based local logistics, and year-round open water on the eastern edge of the domain made this an excellent test bed, with Seagliders first achieving a continuous year of sampling in 2010–2011. As part of the 2014 Office of Naval Research (ONR) Marginal Ice Zone (MIZ) Experiment (Lee and Thomson, 2017), Seagliders occupied sections from deep in the pack to open water, spanning the difficult-to-sample marginal ice zone in the central Beaufort Sea. MIZ gliders navigated from acoustic sources suspended from sea ice, sampling in the drifting reference frame of the ice to maintain collocation with ice-based instruments over a melt season. Most recently, Seagliders have executed missions lasting more than 14 months, operating under ice without communications for periods of up to 10 months near and beneath the Dotson ice shelf in the Antarctic and in the central Beaufort Sea.

Autonomous Underwater Vehicles

Autonomous underwater vehicles (AUVs; Figure 2d) have, over the last three decades, begun to be deployed routinely in polar regions. They have been used for a variety of commercial, military, and scientific under-ice applications, including laying fiber-optic cables (Ferguson, 1998), bathymetric surveys (Kaminski et al., 2010), surveys of the undersides of sea ice (Williams et al., 2015) and ice shelves (McPhail et al., 2009), and for geological and biological surveys at mid-ocean ridges (Sohn et al., 2008).These vehicles are characterized by the lack of a tether and by the fact that they carry relatively sophisticated payloads while maintaining an ability to work in harsh and complex environments with little or no human intervention. AUVs span a broad range of sizes and capabilities, dictated by mission requirements (e.g., Butler et al., 1993; Allen et al., 1997; Furlong et al., 2012).

Extended missions under sea ice require advanced capabilities, such as increased efficiency and the ability to hibernate under the ice to lengthen endurance. Accurate, precise navigation, central to many missions, will depend upon long-range external navigation beacons (e.g., Figure 3d), the use of inertial navigation solutions, or developing techniques to identify leads and then surface and submerge within them. Approaches for mid-mission data transfer mitigate the risk of vehicle loss during extended under-ice deployments. Short range and limited bandwidth render underwater acoustic data transfer impractical, making novel solutions like in-ice docking stations for data and power transfer critical. The partitioning of docking infrastructure between the AUV and the dock has been optimized (Singh et al., 1997), and further advances include the possibility to accommodate multiple vehicles, of different sizes and shapes, at the same dock. The emergence of large buoys designed for use in Arctic sea ice and capable of significant power storage should pave the way for docking technology to progress.

While efforts are underway to conduct autonomous manipulation tasks with AUVs (Fernández et al., 2013), advances in hybrid remotely operated vehicle (ROV)/AUVs (Bowen et al., 2009) have allowed for the physical collection of samples from the ice-water interface and from the seafloor in the ice-covered regions. These vehicles can serve as regular AUVs, but then, using single-use fiber-optic tethers, can be converted into tethered vehicles that allow operators to perform manipulation tasks.

AUV technological innovation, similar to what has taken place in the commercial small-drone community, is needed if AUVs are to become available to a wider user group. These innovations would ideally provide smaller, robust, easy to operate/deploy/recover and logistically light-weight vehicles. This would open up monitoring and repeated sampling opportunities for local communities and non-scientific uses alike, allowing broader use of AUVs within a sustained Arctic observing network.

Acoustic Navigation

Efforts to enhance the performance of acoustic navigation for platforms operating in polar waters focus on improving accuracy, adding flexibility, and increasing range. Broadband signals have been demonstrated to reduce position errors by an order of magnitude in open water applications (900 m to 80 m, root mean square; Van Uffelen et al., 2016). Broadband signaling has been successfully implemented for acoustic navigation of Seagliders operating in the Arctic, providing reductions in position error and the ability to encode source position and a small command set onto the navigation signal (Freitag et al., 2015). The ability to include source position with each broadcast allows the use of mobile navigation sources and provides increased flexibility in the design of navigation networks. Surface ducting and the resulting reflections off the rough ice-ocean interface limits the range of low-frequency acoustic navigation signals. This can be overcome by using very low frequency signals (~10 Hz) whose wavelengths are much longer than the roughness scales of sea ice (e.g., Gavrilov and Mikhalevsky, 2006). At the time of writing, programs supported by the US Office of Naval Research are testing a very low frequency navigation system aimed at providing basin-scale geolocation from a modest number of acoustic sources. Arctic acoustic networks could also be enhanced to provide other critical measurements, including integrated ocean heat content through acoustic thermometry and ambient ocean sound (e.g., Mikhalevsky et al., 2015).

SENSOR TECHNOLOGY AND ARCTIC DEPLOYMENT STRATEGIES

Opportunities/Challenges with Biogeochemical Sensor Technology

Ideally, autonomous biogeochemical sensors could be deployed on the various platforms described in the earlier section on Autonomous Platforms to quantify air-sea CO_2 fluxes, the biological pump, and ecological structure and function. Biogeochemical sensors, however, are only just beginning to be deployed on a scale similar to physical sensors (Bushinsky et al., 2019). Sensors for dissolved O_2, pCO_2, pH, nitrate, and bio-optics (backscatter, chlorophyll fluorescence) are mature technologies (Wang et al., 2019), while in situ prototypes have been demonstrated for dissolved inorganic carbon (Fassbender et al., 2015), total alkalinity (Spaulding et al., 2014), and phosphate (Mowlem et al., 2021). Many of these systems are more analyzers than sensors, with pumps, reagents, and associated plumbing. Complexity, cost, and size scale accordingly, and these systems are challenged to achieve laboratory levels of precision and accuracy. While also complex, in situ instruments for quantification of planktonic populations (e.g., flow cytometry) have provided a wealth of information on plankton dynamics (Hunter-Cevera et al., 2016). However, their large data bandwidths and power requirements generally limit them to cabled, moored observatories (Boss et al., 2022). More affordable modular plankton imaging technology (PlanktonScope) with low power requirements is now available, making its deployment on multiple platforms a possibility (Pollina et al., 2020; Song et al., 2020)

Strategies that have been developed to improve sensor performance include using fluorescence lifetime-based sensing for O_2, mechanical wipers for bio-optical measurements, and renewable reagents for CO_2 and pH sensors. It would be ideal if more analytes could be detected via time-resolved fluorescence like that available using O_2 optodes. Analogous sensors for pH and pCO_2 have been extensively tested, but their performance in marine applications has not been promising (Chu et al., 2020). The current trajectory suggests that future in situ sensors will rely heavily on fluidic-based measurement technology.

A near-term opportunity for improving our understanding of Arctic Ocean biogeochemical processes is to more effectively utilize currently available in situ sensors. Combining sensor data with critical physical parameters such as ice thickness or mixed-layer depth can greatly enhance understanding of biogeochemical variability. For example, in a mooring deployment in the Canada Basin (DeGrandpre et al., 2019), pCO_2 measurements were combined with upward-looking sonar (ULS) and an acoustic Doppler current profiler (ADCP) to quantify contributions to CO_2 variability from ice formation and biological production (based on particle backscatter), respectively. CTD data collected by a nearby ice-tethered profiler were used to estimate mixed-layer depths for computing CO_2 mass balances. These types of studies should become more commonplace as interdisciplinary science evolves and grows.

There is also a need for more effective integration of sensors into existing platforms. Currently, only sensors for dissolved O_2, nitrate, pH, and bio-optics have been adapted for gliders and autonomous profilers. The platforms can also be improved or newly developed to accommodate larger sensor payloads. Longer-term aspirations could include development of biogeochemical sensors that are deployable on unmanned aerial vehicles (UAVs). Surface ocean profiles of temperature and salinity have been successfully collected using a UAV-deployed dropsonde-microbuoy (Zappa et al., 2020). To do this, sensors would have to be smaller and capable of retaining calibration and functionality after being dropped into the ocean. Only time will tell whether such sensor technology will come to fruition.

Air-Ice-Ocean Boundary Layer Sensors

During MOSAiC (Shupe et al., 2022; Shupe and Rex, 2022, in this issue), the surface energy budget was observed using new, autonomous ASFSs. These mobile, non-floating structures were deployed on existing ice floes alongside ITPs, AOFBs, and IMBs, enabling a complete in situ record of the vertical transfer of heat and momentum in the coupled ocean-ice-atmosphere system. In fully coupled models, sea ice evolution is the result of the simulation of these difficult-to-observe, but highly desirable, heat and momentum budgets, and models are increasingly being used in sea ice forecasting (Smith et al., 2019). In particular, air-ice measurements are rarely made autonomously over sea ice and remain missing from most ITP/AOFB/IMB deployments. Recent advances in higher power, year-long unattended platforms and work to optimize operation of sensors exposed to weather are beginning to address this gap.

In the ocean, the AOFB measures current profiles into the halocline, enhancing the ITP time series, as well as direct eddy-correlation heat, salt, and momentum fluxes, typically at 3 m below the ice interface within the surface mixed layer. Local basal melt rates are measured with a high-resolution altimeter and compared to IMB ice temperature profiles and inferred conductive fluxes. In contrast to equivalent atmospheric sensors, ocean sensors do not typically suffer freeze-ups that greatly compromise sensor performance. ASFSs collect measurements for deriving atmospheric turbulent sensible and latent heat fluxes using eddy covariance methodology and the full radiation budget, and feature conductive flux plates that capture the complete air to ice energy transfer. There are several unique engineering problems with the open-air ASFS platform, including preventing damage from wildlife; managing large-volume, continuous data collection; a need to observe an undisturbed area of the surface adjacent to the buoy hull; and strict tolerances for maintenance of level. Historically, one of the biggest challenges has been mitigating icing on sensors. The fundamental limitation is no longer the arctic-hardening technology, which can be robustly operated (Persson et al., 2018; Cox et al., 2021). Rather, the current challenges are support for such technology with limited power resources afforded by autonomy and considerations for stability and communications on a floating platform that becomes ice bound through natural freezing. For example, two recent iterations of AOFBs were deployed with sonic anemometers but lacked sufficient battery power (by a factor of 100) to keep the sensor unfrozen by heating.

The ASFS proved successful for MOSAiC, but was designed for only two months of autonomy using ~65 W. More recent work in collaboration with the ONR Arctic Mobile Observing System program has reconfigured the ASFS to mount to the freeboard portion of the hull of a large spar buoy designed for multi-year survivability. This platform affords far greater power resources than typical buoys, but nevertheless the redesign needed to provide similar performance on ~75% less power. An experimental deployment of one such system was carried out in autumn 2021, and preliminary indications suggest that mitigating ice on a surface energy budget system is likely achievable in winter in the Beaufort Sea using <20 W. This system also features elements of the AOFB and IMB on the same platform, indicating that there is some progress toward consolidation of the "buoy cluster" onto a common platform. Coordinated deployments with complementary Integrated Arctic Ocean Observing System buoys (clouds and aerosols), unattended lidar buoys (Mariage et al., 2017), and the ASFS/IGB-H are desirable, as is coordination with deployments of autonomous surface vehicles sampling the open water side of the MIZ. In the upper ocean, drifting and mobile platforms described earlier can be used to quantify the horizontal inhomogeneity of surface fluxes, which is critical for understanding the under-ice boundary layer.

Systems of Complementary Platforms

Coordinated deployments of complementary platforms and sensors can provide a more comprehensive characterization of the Arctic environment while placing the measurements in broader spatial and temporal context. Ice-tethered platforms are often deployed in clusters to achieve a more comprehensive set of measurements, such as trios of ITPs, AOFBs, and IMBs. Coordination during planning, deployment, and analysis should be expanded to encompass the growing network of in situ platforms. For example, a joint WARM (Figure 4b,g) and IMB (Figure 4c,d) buoy deployment in 2017 traversed the area where three heavily equipped moorings were deployed (Figure 4a). These moorings, part of the Beaufort Gyre Observing System (Proshutinsky et al., 2020), include a subsurface float (~25 m) with an ADCP and upward-looking sonar for quantifying ice thickness. The moorings also have $p\mathrm{CO}_2$, pH, and O_2 sensors below the float, and a deep profiling CTD (Figure 4e,f). Most of these in situ biogeochemical studies are not currently coordinated between researchers and organizations. There are, however, international programs to facilitate and inform the community about other studies such as the Global Ocean Acidification Observing Network (GOA-ON). They gather information about observing assets (http://portal.goa-on.org/Explorer) and link to archived data in the National Science Foundation Arctic Data Center (https://arcticdata.io). Additionally, federally funded researchers have access to high spatial resolution commercial satellite imagery from Planet (Planet Team, 2017) and Maxar (https://www.maxar.com), which provide synoptic observations of sea ice conditions surrounding buoy clusters at spatial scales of hundreds of kilometers on near-daily temporal resolution.

DISCUSSION AND RECOMMENDATIONS

Autonomous platforms and sensors provide critical capabilities for addressing the severe challenges inherent in Arctic observing. Mature approaches, such as ice-tethered instruments, are being refined and enhanced. Other developments focus on adapting platforms that are in common use in the ice-free oceans (e.g., profiling floats, long-endurance gliders) to overcome the operational constraints imposed by sea ice. Novel sensors provide measurements of critical biogeochemical and biological parameters and the atmosphere-ice-ocean boundary layer. The extended endurance and scalability offered by these instruments makes it possible to resolve key spatial and temporal scales that have previously been impractical or impossible to address. While these advances address the needs of climate/policy and strategic/regional scale systems (Figure 1), meeting the demand for geographically focused, persistent measurements, delivered in near-real time, at short temporal and spatial scales for tactical/situational awareness (Figure 1, lower left quadrant) remains challenging.

Continued progress toward meeting the spectrum of Arctic observing needs will require highly scalable instruments that are serviceable with modest, flexible logistics. Effort should be focused on development of low-cost, lightweight platforms and sensors that support a range of operational modalities, with the potential for deployment in large numbers. Such flexible systems could be applied to problems ranging from process studies to climate-scale observing and could adapt in response to changes in the Arctic environment, societal needs, and scientific understanding (Figure 1). The most effective observing systems are likely to be designed using heterogeneous combinations of complementary platforms. Robust, low-cost, operationally simple platforms open a path for regional applications through collaboration with coastal communities, thus broadening the range of people able to assist in the design and maintenance of future observing systems. These developments would also enable opportunistic deployments in more remote regions of the Arctic through agreements with vessels involved in both commerce and tourism as ship traffic increases in the future.

Additional technological priorities should focus in areas with broad impact. Accelerated development of sensors capable of collecting long-term measurements of surface energy budget components and of biogeochemical and biological parameters, ideally at scales similar to those resolved for physical variables, should be prioritized. Underwater geolocation at basin scales, such as that provided by nascent very low frequency acoustic systems, would facilitate operation of a broad range of low-cost autonomous platforms for operation in ice-covered regions. Data exfiltration from instruments operating under the ice remains extremely challenging, but progress in this area is critical for systems meant to support operational modeling.

Measurements must be distributed over the entire Arctic Ocean, including the poorly sampled Russian sector, to take full advantage of the complementary nature of remote sensing and in situ observations. Remoteness makes surveys and instrument deployments difficult. Cyclonic circulation in the Russian Arctic drives divergent drift patterns that rapidly expel instruments from the region. In the future, autonomous profiling floats and gliders may extend our measurements into these remote regions. Another promising approach is increased use of long-range aircraft for float and buoy deployment, perhaps in conjunction with airborne hydrographic surveys using expendable probes (Dewey et al., 2017; Zappa et al., 2020). This suggests investing in efforts to adapt instrument systems described in this section to aircraft deployment over wider areas and more seasons.

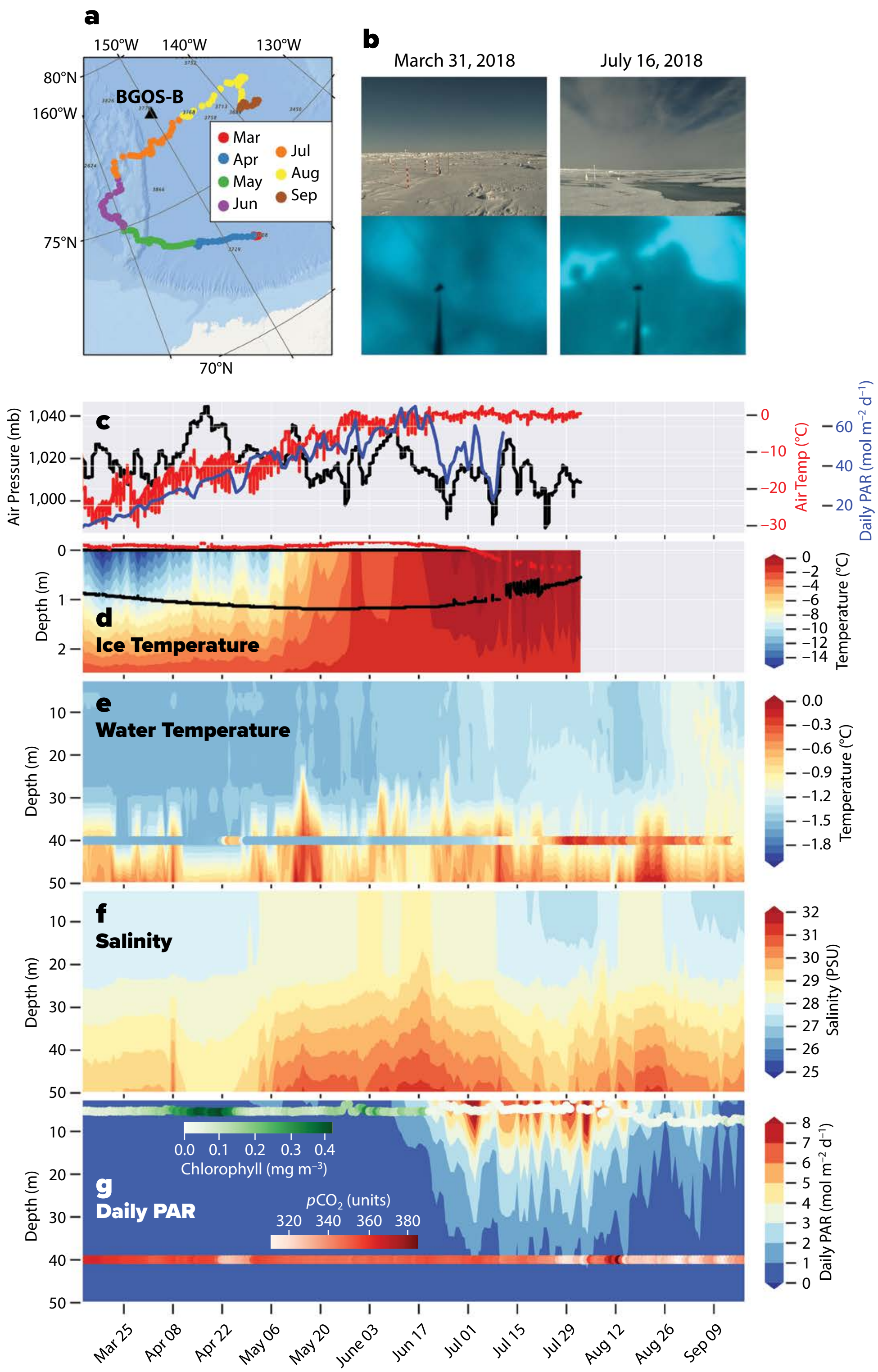

FIGURE 4. (a) Drift track of the WARM buoy and the location of the Beaufort Gyre Observing System (BGOS)-B mooring. (b) Photographs taken from the WARM buoy show views above and below the ice. (c) Air pressure (black) and air temperature both measured by a Sea Ice Mass Balance (SIMB) buoy, along with daily photosynthetically available radiation (PAR) incident on the ice surface measured by the WARM buoy. (d) Ice temperature (contour) and snow surface (red) and ice bottom (black) contours measured by the SIMB. (e) Water temperatures recorded by the WARM buoy with water temperature measured by the mooring overlaid using the same color scheme. (f) Water column salinity measured by the WARM buoy. (g) Daily PAR reaching the water column, chlorophyll fluorescence (green), and pCO_2 (red) measured by the WARM buoy.

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SIDEBAR > CHANGES IN ARCTIC OCEAN CIRCULATION FROM IN SITU AND REMOTELY SENSED OBSERVATIONS

SYNERGIES AND SAMPLING CHALLENGES

By James Morison, Ron Kwok, and Ignatius Rigor

Both in situ and remote sensing observations of Arctic Ocean hydrography and circulation have improved dramatically in recent decades, and combining the two can yield the most complete picture of Arctic Ocean change. Recent results derived from classical hydrography and satellite ocean altimetry illustrate this synergy and also reveal a fundamental in situ sampling challenge.

Prior to 1990, the Soviet Union made extensive in situ observations of the Arctic Ocean using drifting stations and annual airborne hydrographic surveys. Since then, improved instrumentation, especially the development of more autonomous sampling (e.g., using drifting buoys), have greatly expanded temporal coverage, particularly in less remote regions such as the Beaufort Sea. These observations captured an increase in the strength of the Beaufort Gyre anticyclonic circulation and its freshwater content, which are commonly taken as representing Arctic Ocean circulation and freshwater content as a whole (e.g., Hofmann et al., 2015; Proshutinsky et al., 2015).

The pan-Arctic perspective on circulation and freshwater content provided by satellite altimeters, for example, ICESat and CryoSat-2 (Kwok and Morison, 2011, 2016) and the GRACE and GRACE-FO gravity satellites (Morison et al., 2012), points to challenges associated with geographically limited in situ observing. For example, ICESat-derived dynamic ocean topography (DOT) reveals basin-wide circulation before (Figure 1a) and after (Figure 1b) a significant increase in the wintertime Arctic Oscillation index in 2007 (Morison et al., 2012, 2021). Studies that relied solely on extensive in situ data confined mainly to the Beaufort Sea and the Transpolar Drift attributed the 2005/2006 (Figure 1a) to 2008/2009 (Figure 1b) changes in Arctic Ocean circulation to a spin-up of the anticyclonic Beaufort Gyre (e.g., McPhee et al., 2009). In contrast, the broader perspective provided by ICESat altimetry reveals an eastward extension of the trough of depressed DOT that resulted in enhanced cyclonic circulation along the Russian side of the Arctic Ocean, changing the pathways of Eurasian runoff to increase freshwater content in the Beaufort Sea (Morison et al., 2012). Comparison of 2011–2012 CryoSat-2 with 2008–2009 ICESat DOT illustrates the opposite shift after the record Arctic Oscillation minimum in 2010 (Morison et al., 2021).

Presently, analyses based solely on in situ measurements are blind to a fundamental mode of circulation variability because there are so few observations on the Russian side of the Arctic Ocean. Morison et al. (2021) characterize circulation changes over the last 70 years using an empirical orthogonal function (EOF) analysis of annual maps of Arctic Ocean dynamic heights (DH) derived from historical (1950–1989) in situ data (Environmental Working Group, 1997) and satellite altimetry measurements of dynamic ocean topography (2004–2019). Analysis of the anomaly of DH and DOT about the mean winter DH and DOT pattern yields a leading EOF that in its positive (cyclonic) phase is characterized by depressed DOT and cyclonic circulation along the Russian side of the Arctic Ocean centered roughly in the Makarov Basin (Figure 1c). Based on buoys tracked by the International Arctic Buoy Program from 2001 to 2021, the chances of finding any buoy, much less an oceanographic buoy capable of measuring dynamic height or freshwater content, in any 250 km square region (Figure 1c) are lowest in the center of the dominant feature of EOF1 in the Makarov Basin. The chance of finding a buoy there is less than 10%, while the chance of finding a buoy in the Beaufort Sea is 30%–60%. To make matters worse, though EOF1 is overwhelmingly a depression-causing cyclonic circulation change, it also includes a localized positive-bulge-causing anticyclonic circulation change in the Beaufort Sea. Thus, the sense of circulation change (e.g., more anticyclonic) in the oversampled Beaufort Sea is the opposite of the actual sense (e.g., more cyclonic) of the overall change.

These results heighten the importance of sea surface heights obtained from ICESat-2 and the Surface Water and Ocean Topography satellite (SWOT; planned for launch in November 2022). The ICESat-2 mission, launched in 2018 (Markus et al., 2017), yields multibeam laser profiles with 10 m resolution that resolve leads in sea ice and thus provide DOT, ice freeboard, and ice thickness. The SWOT mission will be the first space-borne radar interferometer capable of providing wide-swath height maps—50 km on each side of the nadir ground track—of the open and ice-covered oceans (Armitage and Kwok, 2017). It will observe two-dimensional ocean structures that are previously not resolved by traditional profiling altimeters.

The combination of remote sensing and in situ observations provides the most comprehensive picture of Arctic Ocean circulation. Dynamic ocean topography from satellite altimetry combined with in situ temperature and salinity profiles yields vertical profiles of geostrophic velocity, as well as estimates of heat and salt transports. Drifting buoys equipped

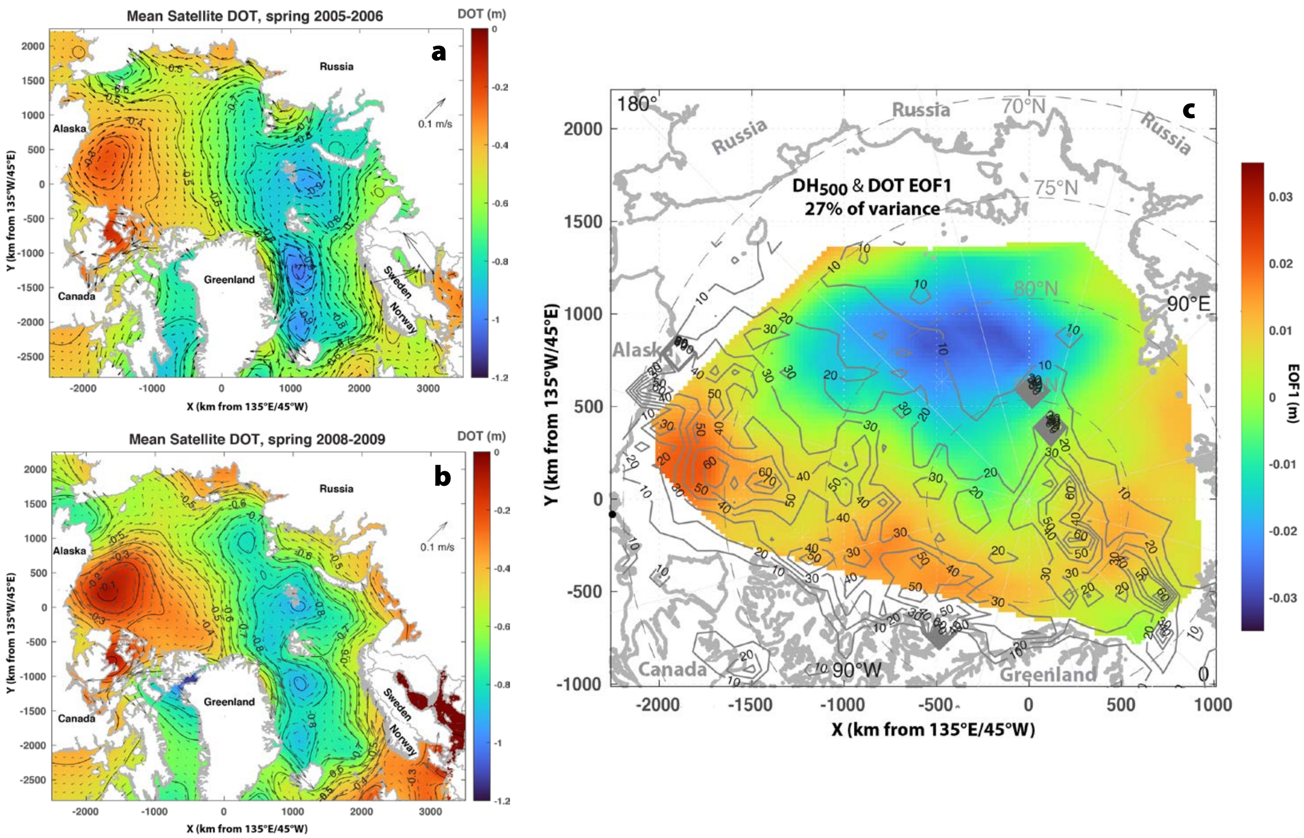

Figure 1. Averages of dynamic ocean topography (DOT) in the Arctic Ocean and sub-Arctic seas for spring (a) 2005–2006 and (b) 2008–2009. (c) The first empirical orthogonal function (EOF) of dynamic heights for the period 1950–1989 combined with DOT from ICESat and CryoSat-2 for 2004–2019 overlain with contours of the percent chance of finding a buoy in any one 250 km square based on International Arctic Buoy Program buoy tracks from 2001 to 2021. *Figure panels from Morison et al. (2021), © American Meteorological Society. Used with permission.*

with high precision GPS receivers will be especially useful for validation of current (e.g., ICESat-2) and future (SWOT) satellite missions.

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SIDEBAR > A YEAR IN THE CHANGING ARCTIC SEA ICE

By Matthew D. Shupe and Markus Rex

Faced with a declining summer sea ice extent, enhanced warming relative to the rest of the globe, altered ecosystem dynamics, shifts in circulation and hydrological patterns, amplifying feedbacks, and potential looming tipping points, the Arctic system is in a transitional state that is at the epicenter of global climate change. As the Arctic transforms, we are challenged to understand the processes involved and to construct the tools and models that will help us predict and manage those changes as they continue to evolve in coming decades. It is upon this backdrop of rapid change that the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC 2019–2020) expedition ventured into the central Arctic sea ice (Shupe et al., 2020). It was an expedition to collect sorely needed observations and to examine the changing Arctic in a new way, with an unprecedented level of detail.

An international team of leading climate scientists designed the expedition to understand the fundamental question: *What are the causes and consequences of an evolving and diminished Arctic sea ice cover?* While sea ice was the central integrator, MOSAiC was very much a coupled system study reaching across disciplines and domains. Drawing upon the expertise of many nations, it examined the physical, chemical, and biological processes that link the atmosphere, sea-ice, ocean system, both driving and responding to the massive changes that are underway.

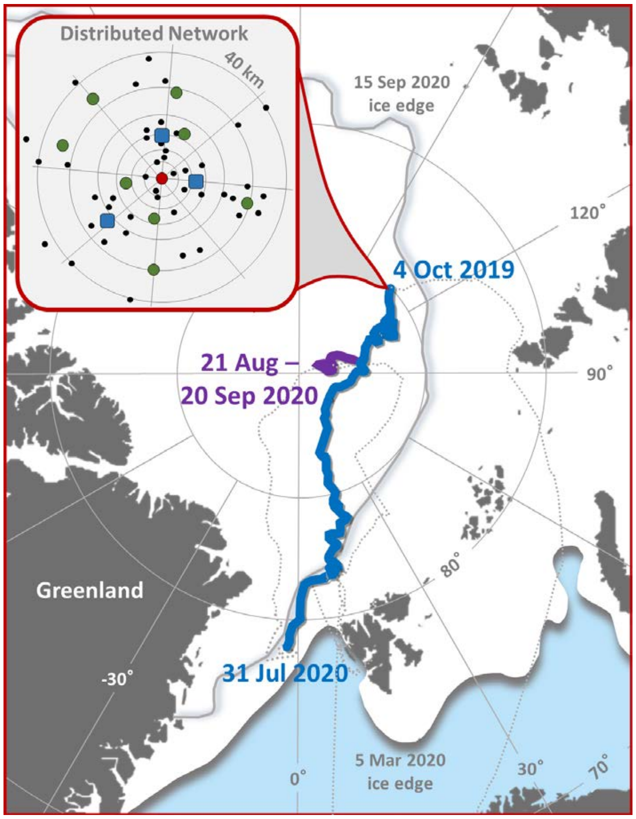

FIGURE 1. MOSAiC drift track with dates and approximate sea ice extent maximum and minimum shown. The inset provides a schematic of the initial distributed network showing *Polarstern* (red) and large (blue), medium (green), and ice-position buoy (black) sites.

Following years of planning, preparation, and coordination, eager MOSAiC scientists embarked on the German research icebreaker *Polarstern* in September 2019, bringing with them an extensive collection of sophisticated instrumentation, extreme weather gear, and observational strategies. After finding a suitable ice floe north of the Laptev Sea, *Polarstern*'s propulsion engines were shut off and the vessel was set to drift passively with the sea ice along the Transpolar Drift (see **Figure 1**), following in the footsteps of Fridtjof Nansen more than 125 years prior.

Polarstern served as a base for the field operations and a stable platform for intensive science (**Figure 2**). Its decks were crowded with state-of-the science equipment, some viewing the clouds overhead or sampling the passing air, while others peered down toward the surface emulating satellite observations of sea ice. Cranes often lowered a rosette or nets down into the adjacent water column. Laboratories hosted devices that probed physical samples of seawater and ice. Every six hours a weather balloon ascended from the helicopter deck. On the ice surrounding *Polarstern*, an extensive network of pathways and powerlines supported scientific installations and sampling. Stations with such monikers as Met City, Ocean City, and Balloon Town were hubs of activity, featuring collections of devices measuring the coupled system away from the adverse impacts of the vessel itself. Zones were identified for ice coring, snow transects, upper ocean profiling, operating underwater vehicles, and much more. Collectively, the components of this central observatory comprised a cross-disciplinary centerpiece of MOSAiC, providing a complex characterization of interwoven climate processes.

Spatial heterogeneity of surface types and other properties affects coupling at a variety of scales and must ultimately be represented in our models. To address this need for scaling, a distributed network was established that stretched for more than 40 km in all directions from the central observatory, in some ways embodying a drifting model grid cell (see **Figure 1**). Comprised of autonomous buoys and sampling devices, this network included a collection of supersites and moderate-sized sites with different combinations of sensors, and an array of nearly 100 position buoys to monitor ice movement and deformation. To place this drifting MOSAiC constellation into the pan-Arctic context, satellite and aircraft observations helped to bridge to larger scales. At the same time, MOSAiC was intentionally equipped with sensors that link to numerous Arctic observing networks with nodes in Svalbard, Alaska, Scandinavia, and elsewhere.

FIGURE 2. July at the MOSAiC ice floe, with *Polarstern* and numerous installations on the ice. *Photo credit: Lianna Nixon*

Like expeditions in the past, MOSAiC was beset by numerous challenges. Ice dynamics were active early and often, forcing numerous re-installations and adaptations of strategy. Frequent visits from polar bears kept scientists alert and cautious. Rapid drift of the ice during the year necessitated a late summer relocation of *Polarstern*. Perhaps the largest challenge, the global COVID-19 pandemic, threatened the expedition at its mid-point and forced dramatic shifts in operational plans. Despite these challenges, MOSAiC persisted.

The year in the Arctic ice was an interesting one scientifically. At least 20 storms were sampled, providing a view into major dynamical shifts in the atmosphere-ice-ocean system, warm air intrusions into the Arctic, and the processes involved in air- and water-mass evolution. An extensive freshwater layer capped the ocean in summer, affecting the vertical distribution of ocean communities and the exchange of gases. Unique platelet ice formations were observed, and internal ice stress was documented. The pan-Arctic circulation characterized by the Arctic Oscillation Index was at record highs in the winter, leading to a particularly strong polar vortex and substantial stratospheric ozone depletion. Importantly, the expedition was able to link processes that played out over a full annual cycle, bridging seasons and characterizing the rarely observed winter in great detail.

The MOSAiC expedition was an incredible success. Scientifically, it broke new ground by offering many observations that are the first of their kind. Programmatically, it embodied the spirit of international collaborative science, leveraging the support of 20 nations toward addressing shared scientific priorities. The expedition helped to build capacity in key ways by training a whole new generation of Arctic scientists and offering new insights into field research on thinning sea ice. Most importantly, MOSAiC has provided a huge legacy of data that will serve the research community for decades to come and provide the foundation for accelerated understanding and improvement of model predictive capabilities in the Arctic. As they are quality controlled and finalized, data are becoming available on the MOSAiC data archive at the German PANGAEA Data Publisher, the US Arctic Data Center, the US Department of Energy Atmospheric Radiation Measurement data archive, the UK Polar Data Centre, the British Oceanographic Data Center, and elsewhere. All data must be finalized and publicly available by the start of 2023. Further information on the MOSAiC expedition is available in overview papers published as part of the MOSAiC Special Feature in the journal *Elementa* (Nicolaus et al., 2022; Rabe et al., 2022; Shupe et al., 2022; and others to follow).

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SIDEBAR > ARCTIC DATA MANAGEMENT AND SHARING

By Peter L. Pulsifer and Craig M. Lee

Established and emerging observing technologies provide the potential for expanding our view and understanding of the many dimensions of the Arctic, including its physical, biological, and social domains. New sensors, platforms, survey tools, and a community-driven monitoring program are generating what is referred to as "big data," a term used to describe not only the size of data resources but also the increasing speed of data collection and delivery, the many kinds of data, and the challenges of establishing the accuracy of these data streams. Without an appropriate system for managing data, observations are ephemeral, and their value is limited.

Data systems are advancing alongside and, in some cases, integrated with observing technologies, with the goal of establishing infrastructure that can support seamless data discovery, access, and usage across data providers and users. Building on decades of development, the current objective is to achieve findable, accessible, interoperable, reusable (FAIR) data (Wilkinson et al., 2016). Moreover, the Arctic is home to Indigenous people who have enduring, unique knowledge and observations of their homeland that are increasingly being documented and shared as part of an evolving integrated observing system. Protocols have been established to ensure that Indigenous people and their organizations are recognized as full partners who are actively engaged in the observing process. The FAIR principles exist alongside the CARE Principles of Indigenous Data Governance—Collective benefit, Authority to control, Responsibility, and Ethics (Russo Carroll et al., 2020)—and other regional and national protocols. These guiding protocols exist as part of an Arctic data "ecosystem" of interrelated and interdependent technologies, information objects, human actors, institutions, norms and practices (including standards), relationships, and the broader sociotechnical environment in which it exists (Parsons et al., 2011; Pulsifer et al., 2014, 2020).

The Arctic data management community is deploying and enhancing technologies and methods to ensure that the Arctic data ecosystem can serve all communities and achieve FAIR/CARE data. Underpinned by the collaboration fostered by the International Polar Year (2007–2009) and the resulting formation of bodies such as the Arctic Data Committee (https://arcticdc.org), a growing consortium of polar data stewards and coordinating bodies are collaborating through workshops, conferences, and working groups to make progress (e.g., Polar Data Forum, https://polar-data-forum.org/, and Polar to Global Hackathon, https://arcticdc.org/meetings/conference-calls-webinars/polar-to-global-online-interoperability-and-data-sharing-workshop-hackathon).

For example, the POLar Data discovery Enhancement Research (POLDER) working group has established a Pilot Federated Search tool (https://search-dev.polder.info/) that uses a shared metadata profile to connect the many different polar data catalogues hosted by data centers and other institutions. This tool dramatically improves the community's ability to find data and provides a gateway to access data. Conventional data download sites are still a common method for making data and associated metadata accessible; however, these sites are quickly being supplemented by the deployment of web services or web-accessible application programming interfaces (APIs). These dynamic, "live" services can support near-real-time access to data that does not require users to download data sets to their local environment. Data are streamed, and many different services can be used in combination to support complex modeling and research, while greatly reducing the time and resources required to manage and process data in a user's local environment. Web services are also contributing to enhanced interoperability—the ability of systems to readily share information and operations. Using standards and specifications such as those developed by the Open Geospatial Consortium (https://www.ogc.org/) and the International Organization for Standardization (https://www.isotc211.org/), data repositories can be connected to incoming data streams generated by new observing technologies, and to different end users including those who are mediating the data (e.g., modelers) or others who may want to simply aggregate data to create broader geographic coverage. Projects such as the Arctic Spatial Data Infrastructure, the Canadian Consortium for Arctic Data Management, and the Global Cryosphere Watch are deploying web services to make data FAIR (https://arctic-sdi.org/, https://ccadi.ca/, https://globalcryospherewatch.org/).

Web services and associated mediation methods are improving data interoperability; however, a major challenge remains—semantic interoperability. Simply transferring data does not guarantee that the exchanged data can be understood and used by the recipient. Data sets include various classes and attributes that have meaning to producers and users, for example, different ocean or atmospheric parameter names, feature classes on a classified satellite image or map, qualitative themes identified and named in a social science research study, and Indigenous knowledge concepts and place names. Interoperability and reuse can only be achieved if the meanings imbued in data elements are explicitly shared along with the data sets. To address this issue, the Vocabularies and Semantics Working Group is collaborating to develop and encourage the tools and methods needed

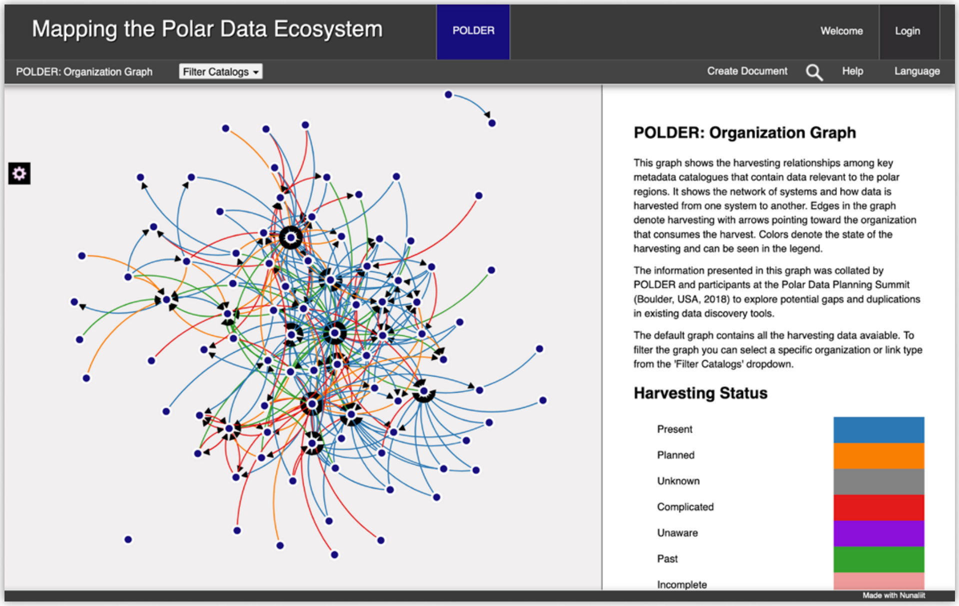

FIGURE 1. The Mapping the Polar Data Ecosystem project (https://develop.gcrc.carleton.ca/mdpe/) aims to use the established conceptual framework of information ecology as an analytical tool to help organize ideas and comprehend the complexity of the Arctic and polar data ecosystem. The associated website provides interactive visualizations of different elements of the Arctic and Antarctic data ecosystems.

to share data semantics (https://arcticdc.org/activities/core-projects/vocabularies-and-semantics-wg).

In the era of big data, accessing and using very large data sets can be challenging for users with limited storage and computational resources. New observing technologies can produce terabytes of data in a single day, and downloading and managing these data can be time-consuming and costly. New platforms that bring the user to the data rather than data to the user are now available to the Arctic community. For example, the Polar Thematic Exploitation Platform (https://portal.polartep.io/) provides a complete working environment where users can access algorithms and data remotely.

Emerging observing and data management technologies have the potential to revolutionize our ability to understand the Arctic and make informed decisions to meet current grand challenges. A key to realizing this potential is understanding and managing the system's complexity to improve collaboration and system integration. The Mapping the Polar Data Ecosystem project, currently a joint effort of the Arctic Data Committee, Arctic PASSION, and POLDER, is working to meet this meta challenge that is fundamental to realizing the FAIR and CARE principles (Figure 1).

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SIDEBAR > FLOAT YOUR BOAT

LAUNCHING STUDENTS INTO THE ARCTIC OCEAN

By David Forcucci, Ignatius Rigor, Wendy Ermold, and Harry Stern

Our understanding of Arctic sea ice and ocean circulation began with the drift of two wooden boats. First, wreckage from the naval exploration vessel USS *Jeannette* was found off the southwest coast of Greenland in 1884 three years after the ship sank in the East Siberian Sea. Second, Fridtjof Nansen's expedition intentionally locked *Fram* in the Arctic sea ice north of the Laptev Sea in September 1893, and it was finally released from the ice's grip in August 1896 north of what is now known as Fram Strait (**Figure 1**). Then, at the turn of the twentieth century, *Jeannette* survivor George Melville introduced a program that deployed wooden casks containing sealed notes to track Arctic circulation. The casks acted as autonomous drifters, similar to today's International Arctic Buoy Programme (IABP) drift buoys, that allow data collection without exposing human lives to the rigors of the Arctic.

Following the legacy of the early Arctic explorers, Float Your Boat (FYB) is a unique and fun outreach program that provides a novel opportunity for students and the public to learn about the Arctic Ocean. Participants decorate toy wooden boats with words and art, and the boats are deployed on Arctic Ocean ice floes by icebreakers. Personal connections to the Arctic develop with the anticipation and excitement of the boats being reported on distant shores years later by beachcombers. The brand "www.floatboat.org" is burned into the wood so that anyone finding a boat can visit the website and report the discovery. In 2015, 1,400 toy boats were cut by the Center for Wooden Boats in Seattle, Washington. Youth from the Pacific Science Center, K–12 schools, and other community groups around the United States participated in personalizing the boats with their individual designs. In 2015, US Coast Guard Cutter *Healy* deployed this inaugural flotilla of wooden boats on the sea ice along the 150°W meridian during a GEOTRACES cruise (**Figure 1**). Students tracked their drift across the ocean in real time through IABP meteorological buoys, deployed at the same time as the boats, using the IABP webpage https://iabp.apl.uw.edu/Float_Your_Boat.html and the project's Facebook page https://www.facebook.com/floatboat.org.

Three to six years after the 2015 deployment, eight of these boats were reported by beachcombers (**Figures 1 and 2**). Boat reports provided the only evidence that the two northern deployment sites were entrained in the Transpolar Drift Stream, because their accompanying buoys stopped reporting very shortly after deployment (**Figure 1**). As boat reports started trickling in three years after the 2015 deployment, a cadre of excited collaborators were inspired to launch more boats.

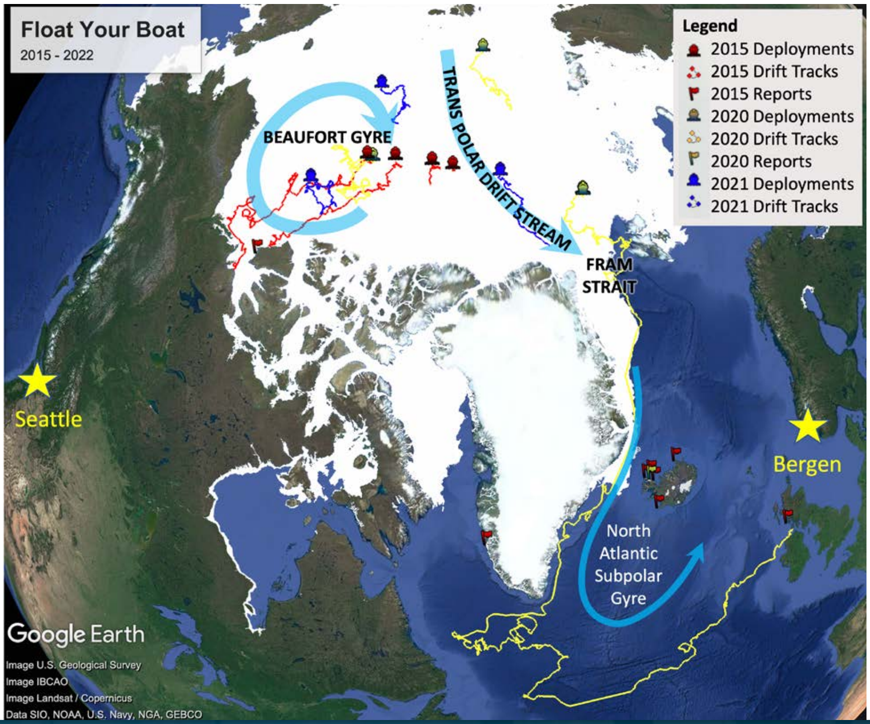

FIGURE 1. Map of drift of buoys deployed in 2015 (red), 2020 (orange), and 2021 (blue) and subsequent beached locations of accompanying Float Your Boat (FYB) program boats (red and orange flags), overlaid on the Multi-sensor Analysis of Sea Ice Extent (MASIE) produced by the National Snow and Ice Data Center and the US National Ice Center. Idealized flows of the Beaufort Gyre, the Transpolar Drift Stream, and the North Atlantic Subpolar Gyre are also shown. Red flags mark the locations of wooden boats reported from the 2015 deployment, and an orange flag marks the first boat reported from the 2020 deployment (The Westfjords of Iceland).

FIGURE 2. (left) Guy Lawrence, sixth grade teacher with Seattle Public Schools, is nearly buried under the Tops K–8 and Eckstein Middle School 2021 fleet of FYB boats collected for loading on USCGC *Healy*. (middle) Tiny wooden boats were placed at the North Pole in September 2021 by NERSC scientists and tourists from the icebreaking cruise ship *Le Commandant Charcot* (heart shape) along with buoy equipment (foreground) provided by the International Arctic Buoy Program (IABP). The boats and buoys then drifted as a unit with the Arctic ice until the ice melted and each component floated away on a voyage of its own. (right) Nando Petersen exhibits a boat he found in August 2019 on an uninhabited island 8 km (5 miles) southwest of Nuuk, Greenland. The boat had been placed on the sea ice by USCGC *Healy* north of Alaska on the 150°W meridian in September 2015. *Photo credits (left to right): David Forcucci, Hanne Sagen, Franz Petersen*

In 2020, just before the global COVID lockdown, hundreds of students gathered at the Pacific Science Center in Seattle, Washington, to ready 550 boats for the Arctic sea ice. The 2020 Coordinated Arctic Acoustic Thermometry Experiment (CAATEX) facilitated collaboration with the Nansen Environmental and Remote Sensing Center (NERSC), which engaged schools in Norway to participate in Float Your Boat. The plan was for *Healy* to deploy boats in the western Arctic and the Norwegian Coast Guard icebreaker K/V *Svalbard* to deploy boats in the eastern Arctic, each during their respective CAATEX cruise. A failure of *Healy*'s starboard main motor required a last-minute change in plans and K/V *Svalbard*, in an impressive feat of seamanship, sailed from Svalbard, Norway, to the Beaufort Sea, via the Northeast Passage, in late fall on a rescue mission to retrieve the CAATEX moorings and deploy boats along the way. K/V *Svalbard* also supported additional IABP deployments during this expedition, filling in IABP coverage gaps and enhancing the synergy between outreach and science.

In 2021, the Float Your Boat program was embraced by Seattle Public Schools (SPS), and hundreds of students participated. The students were learning remotely during the peak of the COVID pandemic, so boats were decorated at home. Teachers incorporated FYB into a wide range of curricula, from arts to science. One SPS teacher had this to say about the program: "Combining art and community partnerships for science data beyond the scope of our own classroom gave context to our learning about Oceans and Climate. Especially following months of remote learning, it was so valuable to have a hands-on relevant experience together."

In 2021, personnel aboard *Healy* deployed boats in the western Arctic, and collaboration expanded with the engagement of the Nansen and Amundsen Basin Observing System (NABOS) cruise on the Russian research vessel *Akademik Tryoshnikov* and the NERSC cruise on the icebreaking cruise ship *Le Commandant Charcot*, which resulted in three deployment locations in the Arctic Ocean (Figure 1) and a total of about 600 boats, each with a number burned into the wood for identification.

Scientific return rates are not the goal of Float Your Boat. Rather, FYB connects people to the Arctic Ocean through personal experiences. The kids' boats get launched into the Arctic Ocean, but it could be the boats launching the kids. Launching a single child into curiosity about the Arctic, or the report of a single boat being found, are both considered huge successes. Float Your Boat has surpassed those expectations with multiple boat reports over the years, and thousands of kids engaged. Most of the wooden boats may never be found—but the FYB experience may last a lifetime.

ACKNOWLEDGMENTS

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Limited Opportunities and Numerous Barriers to Ocean Science Careers in Under-Resourced Nations

By Tashiana Osborne, Charitha Pattiaratchi, and Erin Meyer-Gutbrod

BOTH LOCAL AND international careers in the ocean sciences are largely unavailable or inaccessible to interested students and graduates from under-resourced nations. Barriers to ocean science careers result from a range of region-specific factors. Financial and infrastructural resources supporting ocean science opportunities are limited. Inter- and intranational abuses of power, societal instabilities, and exploitation of communities and resources can create and exacerbate these resource deficits. Access to available resources is not evenly distributed due to societally constructed gaps in opportunity, representation, inclusion, and equity in education and in the geosciences in particular. Ocean careers in under-resourced nations are further constrained by the lack of awareness efforts and examples of real-life, societally beneficial applications of geoscience in education, as well as the absence of specialized mentors and role models.

The educational challenges and opportunity gaps begin in primary school and continue through post-graduate training. Students in under-resourced nations have fewer opportunities to encounter applications of ocean sciences, especially when schools do not have the resources to adequately promote ocean education and conduct awareness-building activities, and teachers lack familiarity with the subject matter. At the higher education level, universities are unlikely to offer ocean science courses due to a lack of demand and few knowledgeable instructors. As a result, students are unaware of the variety of ocean sciences careers, many of which address important societally relevant issues. Globally, few undergraduate programs offer majors in the ocean sciences. Thus, undergraduates worldwide who are interested in ocean sciences, including those from under-resourced nations, often pursue majors in biology, chemistry, physics, and mathematics that take them in directions other than ocean science.

In order to advance their undergraduate training and remain competitive for a wider range of ocean science careers and research, a small percentage of students from under-resourced nations pursue graduate degrees in the ocean sciences or a related field at Western universities. While attending Western universities, these students face barriers to pursuing their degrees that can result from bias, discrimination, and aggressions because of their customs, physical characteristics, and accents, among other traits. Such barriers can challenge students' senses of belonging and can affect the number, type, and quality of training, collaboration, and mentoring options available to them (Beoku-Betts, 2004; Lee and Rice, 2007; Houshmand et al., 2014; Marín-Spiotta et al., 2020). In addition, graduate-degree-seeking students from under-resourced nations face an array of challenges such as language and cultural barriers, immigration and citizenship hurdles, and expensive standards of assessment that do not predict success but can instead present barriers to admission, such as the Graduate Record Examination (GRE; Miller and Stassun, 2014; Petersen et al., 2018; Miller et al., 2019).

The financial burden of graduate school is another obstacle for students from under-resourced nations, so it is often essential to secure a scholarship to cover fees and living expenses. Universities typically charge higher tuition fees for international students pursuing master's degrees, and scholarship and fellowship opportunities are often unavailable to non-citizens. Due to fewer fellowship opportunities, international doctoral students may be provided university funding with requirements to remain active in teaching or research assistant roles. Others may receive support from their home country's government, often requiring the student to either pay the amount back or return to their home country to work for several years post-completion to build or contribute to local programming, research, or teaching initiatives.

As a global community, there are many actions we can take to support ocean sciences education from primary school through post-graduate training in under-resourced nations. Partnerships among nations of differing and/or similar resource levels are essential for ultimately increasing recruitment from under-resourced nations.

Several international and national organizations run programs that include goals or support for building capacity in under-resourced nations (**Box 1**, 1–10). All of these programs are either actions of or alignments with the United Nations Decade of Ocean Science for Sustainable Development (10). Some programs' thoughtfully designed efforts focus on two-way knowledge sharing between local populations and organization facilitators about sustainable fishing practices and aquaculture (e.g., 1, 5, 7, 8, 9). Other programs provide or fund training so that local scientists and technicians can collect and transmit oceanic and atmospheric observations with the goal of improving global ocean and climate predictions (all listed). Several of these programs prioritize establishing or promoting best practices that involve project design and implementation standards and ethical guidelines for equity-centered capacity development initiatives and decision-making processes (e.g., 1, 3, 4, 8). A number of papers outline best practice recommendations for relevant ocean science or policy efforts (e.g., Hagelsteen and Becker, 2019; Vierros et al., 2020; Ferrer et al., 2021; Nyadjro et al., 2021; Urban and Seeyave, 2021; Krug et al., 2022).

Other programs concentrate their efforts on providing invaluable ocean science learning, research, and/or networking experiences (e.g., Box 1, 3, 5, 7, 8, 9,). These efforts include short-term educational and research collaboration workshops, exchange programs, and virtual training in democratized tools and technologies used in the geosciences. Several of these programs provide support and professional development opportunities for students and early to mid-career professionals (e.g., an emphasis of 5, 7, 8) and model or encourage diverse representation in leadership, including those from underrepresented groups both in under- and higher-resourced nations. Ocean Corps, an endorsed program of the UN Ocean Decade, is an example of an organization that promotes projects and collaborations that target all of the above goals on regional to international scales.

Students and professionals from underrepresented, under-resourced, and/or disadvantageously positioned groups worldwide urgently require access to additional training opportunities in the ocean sciences. While the programs listed in Box 1 provide a model for how resources can be shared globally to diversify the field of ocean science, these efforts require increased and sustained attention and support within and between nations in order to continue, improve, and expand. By opening training and career opportunities to participants across the full range of backgrounds and lived experiences, the global ocean science community will be best equipped to fulfill our transboundary responsibilities to humankind and ecosystems.

BOX 1. A Sampling of International Programs Promoting Ocean Sciences in Under-Resourced Nations

ORGANIZATIONS

1. International Oceanographic Commission (IOC, https://ioc.unesco.org/)
2. Ocean Teacher Global Academy (IODE, https://classroom.oceanteacher.org/)
3. Partnership for Observing the Global Ocean (POGO, https://pogo-ocean.org/)
4. Scientific Committee on Oceanic Research (SCOR, https://scor-int.org/)
5. University of Rhode Island Coastal Resources Center (URI CRC, https://web.uri.edu/crc/)

OCEAN DECADE-ENDORSED PROGRAMS

6. Deep Ocean Observing Strategy (https://deepoceanobserving.org/)
7. Early Career Ocean Science Professional Network Program (ECOP, https://www.ecopdecade.org/)
8. Global Ocean Corps and Conveyor (Ocean Corps, https://globaloceancorps.org/) and the Coastal Ocean Environment Summer School in Ghana (COESSING, https://coessing.org/)
9. Ocean Biomolecular Observing Network (OBON, https://www.obon-ocean.org/)
10. United Nations Decade of Ocean Science for Sustainable Development (https://www.oceandecade.org/)

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TEACHING OCEANOGRAPHY BY ENGAGING STUDENTS IN CIVIC ACTIVISM

By Bruce C. Monger

I teach an introductory oceanography course at Cornell University that delivers the basic concepts found in most introductory oceanography textbooks, and also emphasizes, more broadly, the ocean's role in maintaining Earth's overall life support system. The class offers the opportunity to describe how climate change and other human-caused impacts are threatening this system with astonishing speed. The class has grown in popularity over the years, with an enrollment that now exceeds 1,000 students. It is held in the large concert hall on campus (**Figure 1**) and consistently ranks as the largest enrollment course at Cornell. Here, I share some of my thoughts as to why this class continues to attract so much student interest.

The semester initially progresses along the familiar path of presenting basic concepts in marine geology, physical oceanography, biological oceanography, and marine chemistry. However, whenever possible, I pause to explain how a given aspect of the ocean is vital to the planet's—and the students'—well-being (e.g., heat transport by conveyor belt circulation or the biological carbon pump). Presenting these basic concepts consumes about two-thirds of the semester and builds a strong conceptual foundation. After a picture of the vital role the ocean plays in Earth's overall life support system comes into view, I begin to describe a wide range of human-caused threats facing the ocean. These threats include global warming, ocean acidification, ocean deoxygenation, coral bleaching, overfishing, and nutrient pollution. I explain that each of these threats has a solution and that it is a matter for our society, and especially government leaders, to implement these solutions.

I think the class is popular for several interrelated reasons. Course evaluations include a lot of comments about my passionate teaching style, about how I make an emotional connection with students, and about how well-organized lectures are. But the thing that hooks students the most is that I ask them to rise up and become civically engaged with the global environmental issues of our time. This call to action gives students a sense of ownership for what they learn in the class. Instead of simply memorizing ocean facts to replicate on an exam, they are asked to take those facts and work toward making a better world.

The lectures include a lot of inspiring language, and this is especially true in the last third of the semester. As an example, after discussing the short timeline that we face to eliminate carbon emissions in order to limit global warming to 1.5°C, I will say, "Every so often a generation is called upon to do something extraordinary. In 1940, a generation was asked to rise up and fight a world war to save democracy. And now,

FIGURE 1. As this 2014 photo attests, Cornell's introductory oceanography class, taught by the author, is so large it takes place in Baily Hall, the university's concert venue. *Image credit: Kathie Hodge, Cornell University*

once again, a new generation, this generation, is called upon to do something even more extraordinary—to rise up and decarbonize the global energy system by mid-century to save all of humanity."

During the concluding third of the semester, the lectures emphasize the need to raise our voices in collective social action to push government leaders to act on the global environmental threats we all face (Figure 2). I remind students that women in this country did not get the right to vote without campaigning for what was socially just. And African Americans did not get civil rights legislation passed without raising their voices for what was socially just. I go on to say that we will not get a sustainable planet that is socially just for this generation, and for future generations, unless we also collectively raise our voices.

FIGURE 2. Author Bruce Monger traveled with a busload of Cornell students to the March for Science protest in Washington, DC, in 2017.

I believe strongly in the idea that a democracy operates best with a well-informed citizenry. But a well-informed citizenry alone is not worth much if citizens do not also raise their voices to give government leaders their thoughts on how best to move the country and the world forward in a positive direction. In the case of college students, there is an extra, special obligation to raise their voices because they are among the best and the brightest our society can collectively produce. Consequently, their ideas and opinions on how best to move things forward have exceptional value to our society and, therefore, they urgently need to be heard.

I tell students in the oceanography class that they may have worked hard to get to Cornell, but that our society (both past and present, and international) also worked hard, and made significant sacrifices, to build a university that allows them an opportunity to reach their full academic potential. As a consequence, they are obliged to give something back to society. In my opinion, there is an unspoken contract between a society that builds a university and the students who attend that university. Students who enjoy the rewards of a college education and achieve a high level of academic excellence owe the society their voices and opinions on how best to make the world better for everyone in the society.

To emphasize this point, students in the oceanography class have an end-of-semester assignment to write letters to their two United States senators and their congressional district representative in which they express their personal views about an ocean conservation issue of their own choosing. International students are encouraged to write letters to their own respective government leaders. The letter is graded based only on the sincerity of the writing and not on a particular stance the student takes. It is emphasized that the letter should be their own personal views and opinions and certainly not a classic end-of-semester term paper. In short, a student can say whatever is on his or her mind and get full credit. It is up to each student to decide later whether to go ahead and mail their letter. Many students do end up sending their letters. I often receive email after the class is over from an excited former student telling me of a senator's or representative's response—obviously a very empowering experience for a student. The letter writing assignment provides a tangible example of raising your civic voice, and it gives students in the oceanography class something that I call "ownership" of the material they have learned in the class.

And I would argue that taking ownership elevates long-term retention of the class material.

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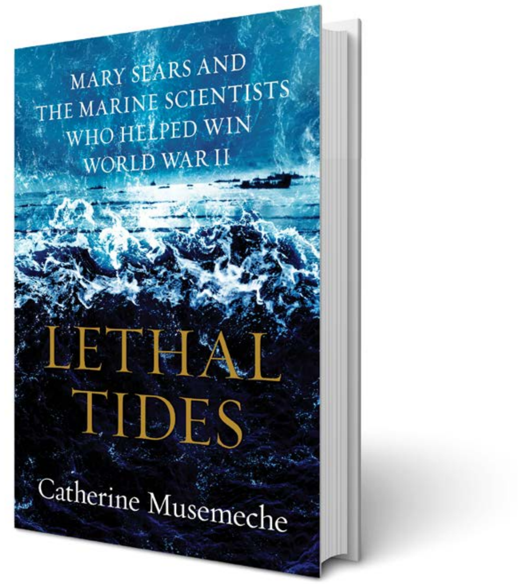
LETHAL TIDES

MARY SEARS AND THE MARINE SCIENTISTS WHO HELPED WIN WORLD WAR II

Book by Catherine Musemeche, 2022,
William Morrow, an imprint of Harper Collins, New York, NY, USA,
304 pages, ISBN: 978-0-06-299169-0, $28.99 USD

Reviewed by D. James Baker



Although Thomas Jefferson had recognized the need for mapping and charting the waters of the young United States in 1807, it wasn't until 1830 that the US Navy established the Depot of Charts and Instruments, which later became the US Naval Hydrographic Office. At the beginning, the Depot was a clearinghouse for navigational equipment and the few foreign charts that were available. The Depot didn't make its own charts until 1837, with the first one covering Georges Shoal and Bank, from ship tracks provided by Lt. Charles Wilkes. Wilkes later led the famous 1838 US Exploring Expedition that provided the United States its first worldwide mapping coverage (Heynen, 1978).

But the supply of information continued to be limited. Even in the late 1930s, as the United States anticipated conflict in the Pacific Ocean with Japan, it was apparent to Navy leadership that the country lacked critical oceanographic information needed to fight at sea. The Navy had called up Roger Revelle of Scripps Institution of Oceanography in 1941 to work on sonar, then reassigned him in 1942 to the Hydrographic Office. More interested in working at sea, Revelle recruited Mary Sears from the Woods Hole Oceanographic Institution (WHOI) to build a team that would focus on the necessary oceanographic science and metrics needed for Allied operations.

For Mary Sears, this was the beginning of an influential career that touched most of the marine science community in the world. The detailed story of how she stepped out of her laboratory role as a plankton expert and built a team to help win the war is just the first part of that career. The story has now been described in depth in a new book *Lethal Tides: Mary Sears and the Marine Scientists Who Helped Win World War II* by Catherine Musemeche. The book vividly recounts those eventful years when Sears and her team of ocean experts scoured the world for critical ocean information and made it available for use in the war.

After a brief early life history, the book focuses on the efforts it took to get a woman into the Hydrographic Office after a long history of misogyny, and then shows how Sears used her knowledge of people and expertise to pick just the right team and to manage a successful effort. A brief epilogue for each team member highlights later individual accomplishments.

The team that Sears put together included barnacle expert Dora Henry and her colleague Mary Grier, the University of Washington oceanographic librarian, as well as crustacean expert Fenner Chace of the Smithsonian Institution. The scientists had to set aside their own scientific interests and focus on collecting, collating, and evaluating oceanographic information on beaches, tides, topography, seas and swells, bottom sediments, currents, salinity, and other environmental characteristics that were critical for invasions. Under constant pressure and time constraints and faced with limited data availability, the team, thanks to Mary Sears' knowledge and leadership, was able to provide the necessary critical information for the conduct of the war. In fact, given her successful efforts, Revelle later said that Mary Sears was "the first Oceanographer of the Navy in modern times" (Revelle, 1980).

The story is a gripping one, replete with the pressures of timed invasions, multiple targets, and impossible deadlines. The team had to sort through thousands of scientific papers and reports to find the critical information they needed. Much of it came from the Japanese oceanographic literature, which fortunately was mostly published in English. But the only information they had about some of the Pacific Islands dated back to the Wilkes expedition.

The descriptions of amphibious landings, both the technical difficulties and the human responses, are realistically drawn from eye-witness accounts. The author shows how the Navy learned from early casualties and equipment malfunctions to focus on what information was required to improve the capability to land safely. For example, Sears and her team had to override initial reports of firm beaches for the invasion of Okinawa because they had collected other conflicting information showing that the beaches would require landing mats to support an amphibious landing. The team's research, provided in the "Submarine Supplements to the Sailing Directions," enabled US submarines to hide in thermoclines to escape enemy detection.

The book is written in a narrative style, with much of the information and conversations documented by published personal recollections. But it appears that the author has also imagined some thoughts, scenes, and remarks that are not documented. For example, on page 85, we learn that Sears "crisply saluted" and "the sunlight streaming through the windows reflected off the gold buttons" These are scenes that could have happened but are not documented in the endnotes. Although the endnotes have many references, the book has no bibliography. This omission seems to be more and more common these days as publishers try to save money by printing less. Checking sources has become harder and harder.

And speaking of sources, the author's description of ocean and weather forecasts for the D-Day invasion could be usefully updated with recent work by Anders Persson (2020). Persson uses previously neglected sources to show that most of the common perceptions about those forecasts need to be re-evaluated.

Musemeche's book is an important addition to the history of marine science. It recalls a critical period in US history and gives us a sense of the scientific leadership and organizational abilities of a distinguished marine scientist and her colleagues. But it reflects only a small part of the many accomplishments of Mary Sears who returned to WHOI for a long and award-winning career. She was the founder and editor of the prestigious journal *Deep-Sea Research*. In 1959, she organized the first International Oceanographic Congress at the United Nations that, in Revelle's words, "played a major role in creating the present world community of oceanographers from numerous countries and almost as many specialties. Many of these scientists met with each other and exchanged ideas for the first time at that Congress" (Revelle, 1980).

The book mentions the fact that a US Navy hydrographic ship was named in honor of Mary Sears and went into service in 2001. It's interesting to note a fact not mentioned that in January 2007 the USNS *Mary Sears* was the search vessel that discovered the signals from the cockpit voice recorder and wreckage of the missing Adam Air Flight 574 in waters near Indonesia (Wikipedia, 2022).

Although Mary Sears has been recognized in many ways for her work in the oceanographic community, the oceanographic literature still lacks a full biography of this important scientist and leader. One of the first staff members of the Woods Hole Oceanographic Institution, she was the first recipient of WHOI's Women Pioneers in Oceanography Award, and the award was then named for her. The award recognizes "long-term, life achievement and impact, with special consideration given to candidates who also have shown leadership through mentoring junior scientists, technicians, or students" (WHOI, 2022). (On a personal note, I first met Mary Sears at Woods Hole in 1969 as a young visiting scientist. I found her a formidable person, but very helpful with advice, and I was thrilled when I published my first paper in *Deep Sea Research*. I was also an admiring colleague of Dora Henry at the University of Washington and found her sage advice helpful as we formed a new college there.) Of course, members of The Oceanography Society have already made their tribute to this remarkable scientist through the Mary Sears Medal awarded biennially to an ocean scientist who "has made sustained, innovative, and impactful contributions to original research in the areas of biological oceanography, marine biology, or marine ecology, along with outstanding contributions to education and mentorship in the field."

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CAREER PROFILES Options and Insights

Regina Easley-Vidal, Research Chemist, National Institute of Standards and Technology (NIST) and Adjunct Professor, Georgetown University – regina.easley@nist.gov

Degree: When, where, what, and what in?

I earned a bachelor of science degree in chemistry from Hampton University in 1999. After leaving Hampton, I traveled west and earned a master of science degree in organic chemistry from the University of California, Los Angeles. I worked in the pharmaceutical industry for two years following that degree as a quality assurance/quality control chemist for two generic drug manufacturers. I knew those positions were not what I wanted long term, and I soon continued looking for opportunities to further my education. I had an early love for marine science, especially during high school where I had an influential environmental science teacher. I was elated to learn about the graduate program in marine science at the University of South Florida (USF) from one of my Hampton classmates. I left industry to pursue my interests in helping to develop in situ colorimetric sensors to study nutrients and the carbon dioxide system in seawater. I could not have imagined that the choice to follow my old passion would take me on an amazing journey. During my time at USF, I participated in several cruises in the Gulf of Mexico and one to the Arctic. I earned my PhD in chemical oceanography in 2013.

Did you stay in academia at all, and if so, for how long?

I dabbled in academia following the completion of my doctorate degree. I did not have a position in place post-graduation, so made the wild decision to challenge myself by teaching chemistry as an adjunct faculty member at four different schools in the Tampa Bay region—all in the same semester. I literally taught seven different classes at four different campuses. After accepting a postdoc offer from the National Institute of Standards and Technology (NIST), I paused teaching to focus on my new role as a research chemist. Ironically, I am back in academia as an adjunct faculty member at Georgetown University, teaching "Introduction to Environmental Metrology" for a new master's program called Environmental Metrology & Policy (EMAP). The EMAP program is part of my official duties and is a collaboration between Georgetown University, NIST, and the US Environmental Protection Agency.

How did you go about searching for a job outside of the university setting?

While looking for jobs, I applied to every opportunity that fit my research interests. I found opportunities on mailing lists from various professional societies and groups and positions posted by my college. Although I have always been interested in academia, none of the positions that I applied for worked out. One of my mentors suggested that I look for federal fellowships offered through the National Research Council Research Associateship Programs (https://sites.nationalacademies.org/PGA/RAP/). One listed at NIST was an ideal fit for my background. At the time, NIST was expanding their capabilities for assessing the traceability of carbon dioxide and pH measurements in seawater. The person who would become my postdoc advisor had even read one of my papers and had attended a meeting with my doctoral advisor. The position was a natural fit.

Is this the only job (post-academia) that you've had? If not, what else did you do?

Yes, this is the only job post-academia that I have held. I was fortunate that my postdoc advisor was transitioning to retirement when I arrived. While I worked on my postdoc project, I also trained on other aspects of his position. After his retirement, I was equipped to take over some of his former projects, and my postdoc position was later converted to a full-time federal appointment.

What is your current job? What path did you take to get there?

My current title is Research Chemist at NIST. I have maintained this role since I started my postdoc there in 2014. NIST is the US national metrology laboratory and is responsible for the distribution of over 1,300 Standard Reference Materials (SRMs). My lab is based in the Chemical Sciences Division, which is part of the Material Measurement Laboratory. I work as an electroanalytical chemist, responsible for certifying pH SRMs and other standards, such as providing certified values for chloride ion in human serum. We maintain high-quality measurement capabilities and in doing this, we participate in international interlaboratory comparisons on a regular basis.

Over the years we have developed partnerships with oceanographic researchers funded by NOAA. I recently became a member of the Interagency Working Group on Ocean Acidification, where I serve on a small committee working to create a sustainability plan for ocean carbon dioxide reference materials. In addition to this, I have teaching responsibilities during the spring semester. Prior to teaching for EMAP, I also had the opportunity teach a short course on pH metrology at the University of Cádiz in Spain. My position is a nice balance of laboratory work, teaching, advising, and policy.

What did your oceanographic education (or academic career) give you that is useful in your current job?
My oceanographic education is foundational to informing our independent research projects. My knowledge of chemical oceanography and some of the challenges associated with measuring the carbon dioxide system have helped us to frame valuable metrological research questions. Courses I took in ocean policy and observing systems give me context for understanding the role of the federal government in ocean management and the connectivity of bodies that manage ocean observing. A lot of these groups are now stakeholders that inform us on the development of oceanographic reference materials.

Is there any course or other training you would have liked to have had as part of your graduate education to meet the demands of the job market?
Looking back, I see how helpful it would have been to take more programming and data science classes in tools like R, ArcGIS, GitHub, and Python. In my position, we generate tons of data, and it is essential to know how to efficiently process the data.

Is the job satisfying? What aspects of the job do you like best/least?
This position is absolutely satisfying! I enjoy the fact that I have multiple opportunities to stay connected with the oceanographic community. I truly feel that the work we are doing to improve the state of reference materials in oceanography is vitally important and will help to sustain our confidence in the data that so many labs around the world are generating. I also appreciate the balance between lab work at NIST and embracing my love of teaching. I feel privileged to be a part of the unique EMAP program and to serve by educating students in environmental metrology. One of the things I like least about the position is administrative paperwork. We work under a quality system that requires constant updating of documents and continual reviews.

Do you have any recommendations for new grads looking for jobs?
My recommendation to new grads is to stay flexible in your search. From my experience, although there are numerous opportunities for working in both industry and government, professors/advisors tend to be more familiar with academic positions. It is also important to stay engaged in your network by attending scientific meetings, being involved in professional societies, and participating in working groups. Many of these groups are willing to involve early career scientists in their planning to bring new ideas and energy.

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Image credit: The Pew Charitable Trusts

Sarah Close, Officer, Lenfest Ocean Program, The Pew Charitable Trusts – sclose@pewtrusts.org

Degree: When, where, what, and what in?
After completing my bachelor's degree in biology and environmental studies at Bowdoin College, I spent about two years in Seattle working for a small nonprofit focused on watershed restoration. I returned to academia and completed my PhD in zoology at Oregon State University in 2014. My dissertation research focused on understanding how oceanography and environmental conditions influence rocky intertidal communities across different spatial scales.

Did you stay in academia at all, and if so, for how long?
I went into academia knowing that I wanted the depth of research experience that it would offer but I was not set on following an academic career path. Early in my PhD, I learned about the year-long Knauss Policy Fellowship that places scientists in policy positions in the legislative and executive branches of the US government in Washington, DC. It sounded like a great way to try out a new field that I was interested in, so when I got close to finishing, I applied for the fellowship and was selected. I moved to DC to start the fellowship at NOAA just three weeks after defending my dissertation.

How did you go about searching for a job outside of the university setting?
The Knauss fellowship really opened doors for me, both in terms of building a professional network and learning a

lot in a short period of time about what opportunities were out there and what interested me. During my fellowship and then working at NOAA for two years, I took note of the elements of my role that excited me and that I wanted to maintain as part of my career going forward. This was useful when the opportunity came along to move to the Lenfest Ocean Program. I had met my now-colleagues at a workshop while working at NOAA, and the more I learned about the Lenfest Ocean Program over the following years, the more I could see that it had the potential to be a great fit for me in the future. I kept in touch with the program, and my current position became available right around the time I was feeling ready for a new opportunity, so I applied, and the timing worked out very well.

Is this the only job (post-academia) that you've had? If not, what else did you do?

During my Knauss fellowship year I worked at NOAA's Climate Program Office supporting the Regional Integrated Sciences and Assessments (RISA) program, a competitive grant program that funds regional teams around the country to conduct interdisciplinary research on climate impacts and adaptation. I loved my experience during the fellowship. I began talking to my manager early in the process about the potential of staying on at the end of the fellowship, and I was fortunate that there was a viable way for me to do that.

After my fellowship ended, I continued working at the Climate Program Office in support of the RISA program and also expanded my portfolio to work in the Coastal and Ocean Climate Applications (COCA) program as well. I had so many valuable experiences during my time in this role, including co-chairing the Adaptation Science Interagency Working Group at the US Global Change Research Program, co-editing a book that documented stories and case studies from across two decades of the RISA program, and getting to know a new field and new community of researchers dedicated to making science useful. In 2017, I left government and moved to The Pew Charitable Trusts. Leaving NOAA was a hard decision as I really believed in public service and the work we were doing, but I had a wonderful opportunity to grow my career.

What is your current job? What path did you take to get there?

I am a program officer at the Lenfest Ocean Program, which is managed by The Pew Charitable Trusts in Washington, DC, where I have worked since 2017. The program is centered on the concept that science is more likely to be used if it is designed to engage users from the beginning. I develop and manage a portfolio of research grants focused on understanding the impacts of climate change on the ocean and providing usable information to address these impacts.

My experience working with the RISA program at NOAA gave me the language to express what had always interested me about working at the science-policy interface and introduced me to a new way of doing science that meets the needs of stakeholders and decision-makers and is conducted hand-in-hand with the people who will use it. I learned so much about funding science, science policy, and usable science working at NOAA. But I was also often working on topical issues for which I had limited background—for example, around drought and water resources—and I missed working on marine systems. The opportunity to work for the Lenfest Ocean Program allowed me to continue working in usable science while also returning to my roots in marine science.

What did your oceanographic education (or academic career) give you that is useful in your current job?

To start with the obvious, graduate school taught me how to really dig into a topic, ask questions, and conduct and evaluate research—skills I use daily as a program officer. But doing research also prepared me for understanding and tracking project budgets, training and managing others, and managing projects by adhering to timelines and budgets. I also taught undergraduate lab courses as a TA, and while there's really no context in which I still need to know how to dissect a pig (for which I'm thankful), I do use the skills I developed in teaching frequently when explaining and translating complicated concepts.

Is there any course or other training you would have liked to have had as part of your graduate education to meet the demands of the job market?

First, I want to point out that your training doesn't stop after graduate school. There will be plenty of on-the-job learning and training opportunities that will allow you to expand your skillset. There are a few skills I would have benefited from during graduate school and in job searches had I learned them earlier. Facilitation skills are incredibly valuable and can be helpful in many different settings and contexts. In my experience, people who are good at facilitation are often highly sought after. I have also seen the value of trainings on self-assessment and understanding your strengths and how you work best, as well as how you can work most effectively with a diverse group of people, an area where there is always room for growth.

Is the job satisfying? What aspects of the job do you like best/least?

I love my job. It is a great fit for me in a few ways. I love working at the science-policy interface and being able to focus on scientific research, how the research is used, and how it can be designed to be most useful. I'm always learning new things as I frequently talk with people about their work and ideas as well as the obstacles they face in bringing science to bear on challenging issues. I enjoy working on climate adaptation—it's a hard space to work in but it is also is very energizing, and so many amazing advances are being made. Finally, I really like working on a diversity of topics and in a range of regions and parts of the world, although staying on top of multiple fields and working on multiple topics simultaneously is also one of the most challenging parts of the job. Hands down, the thing I like the least about my job is turning down research applications for funding. I know how much thought and hard work goes into them, and they are always hard decisions on our end.

Do you have any recommendations for new grads looking for jobs?

Think about what you might like to do as well as what you want to learn or try. Regular self-reflection can help you be more prepared to identify opportunities that would be a good fit when you see them.

Talk to people. It's sometimes hard to know where to start, but it truly is one of the best ways to start looking for a new job. It's perfectly acceptable to cold-email people with whom you might like to talk in order to learn more about what they do, and you might be surprised how willing they may be to have conversations with you. And remember that your network also includes peers who can be great sources of information and advice.

Bear in mind that career paths often sound well planned and linear in retrospect, but the reality is that there are many different ways to create the career you want. Paying attention to what energizes and motivates you and knowing yourself is important, as is remembering that you don't have to figure it out all at once or all on your own.

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