FROM THE GUEST EDITORS

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.

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