BAMS
Meeting Summary

The Arctic Ocean's Changing Beaufort Gyre System

An Assessment of Current Understanding, Open Questions and Future Research Directions

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A Workshop on the Changing Beaufort Gyre System

What: An international group of 50 scientists met in person to review and discuss the physical and biogeochemical aspects of the Arctic's Beaufort Gyre system, explore the open research questions, and make recommendations for future research directions and projects.

Where: Woods Hole, Massachusetts

When: 22–24 March 2023

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The workshop marked the milestone of two decades of intensive sampling of the Arctic Ocean's Beaufort Gyre system. This included the Beaufort Gyre Observing System (BGOS) funded by the National Science Foundation (NSF), a collaboration between U.S. and Canadian scientists under the Joint Ocean Ice Study (JOIS) program. A second NSF-funded Arctic Observing Network program, begun roughly the same time as BGOS, investigates the adjacent boundary current system of the Beaufort Sea. The Beaufort Gyre is one of the fundamental sea ice and ocean circulation systems of the Arctic Ocean, located in a region that is exhibiting some of the most pronounced changes due to the warming climate; for example, the past two decades have seen the largest Arctic sea ice losses and ocean heat content increases in the Beaufort Gyre region and surrounding marginal seas, changes which have important consequences for ecosystems within and beyond the Arctic.

The workshop was attended in person by 50 participants from 7 countries to assess our current understanding of the physics and biogeochemistry of the Beaufort Gyre system, including its boundary and source regions, to discuss open questions and gaps, and to conceptualize future studies. Approximately half of the scientists were in the early stages of their careers.

The 2.5-day workshop began with an overview of the accomplishments and new understanding of the Beaufort Gyre system including outcomes from international collaborations, and then consisted of presentation and discussion sessions on the following themes: Arctic sea ice; Beaufort Gyre source waters, dynamics, freshwater content and change; ocean fluxes, water pathways, and energy distribution; ocean acoustics in the Beaufort Gyre region; and biogeochemical processes and change. A poster session was held on the first day, with the posters remaining up for the duration of the workshop. The last half-day consisted of two breakout sessions in four separate groups such that each group included a range of expertise and backgrounds, experiences, and career stages. Report-outs to capture the main themes were heard from each group. The aim of the first breakout session was to brainstorm the following questions: *What are the major open scientific questions, and what are the critical gaps in our analyses and observations?* The second breakout focused on contemplating: *What new observational approaches can be effective? What is needed with respect to new model development, model inter-comparison analyses and experiments?*

Scientific highlights

Marked changes in sea ice in the Beaufort Gyre system in recent decades were showcased and discussed extensively. The decades-long record of Ice Mass Balance buoys (Perovich 2022) deployed in the Beaufort Sea region has revealed the dominant contribution of bottom ablation and the critical importance of the timing of melt onset in governing ice loss. In the recent decade or longer, the region has transitioned from having predominantly thick multiyear sea ice to much lower concentrations of new, thinner ice—although with complex interannual variability in transport of multiyear ice through the region (Moore et al. 2022; Babb et al. 2022). This shift to thinner and younger sea ice is associated with an increase in winter openings (leads) in the sea ice pack (Rheinlænder et al. 2022). Analysis of these trends has been further refined with improved satellite altimetry sea ice-thickness inferences, information that has been used to evaluate global climate model representations of sea ice thickness distribution (Smith et al. 2022).

Changes in the ocean component of the Beaufort Gyre system are as considerable as its changing sea ice, including increases in freshwater and ocean heat content (reviewed by Timmermans and Toole 2023). These changes relate to the Beaufort Gyre system undergoing distinct dynamical redistributions, spatially and in depth, associated with large-scale wind patterns and source water pathways (Lin et al. 2023). The Beaufort Gyre response to wind forcing is moderated by an active eddy field (Regan et al. 2020), including a distinct seasonal cycle of surface-ocean eddies that relates to that of sea ice cover (Meneghello et al. 2021). With respect to understanding water pathways in the region, recent progress has been made using nuclear reprocessing tracers (Casacuberta and Smith 2023) and oceanic signatures of mixing in context with the large-scale Beaufort Gyre circulation (Shibley and Timmermans 2022). Finally, ocean warming in the Beaufort Gyre region has motivated increased attention on the use of ocean acoustics, with recent halocline warming giving rise to a subsurface sound-speed duct, and ice cover changes influencing ambient sound (Worcester et al. 2022).

Recent modeling results were discussed, including coupled high-resolution simulations from the Naval Postgraduate School Regional Arctic System Model (Maslowski et al. 2020) that demonstrate the importance of resolving smaller-scale oceanographic features, such as boundary currents, that affect the entire system. Progress has also been made on understanding change with the Estimating the Circulation and Climate of the Ocean state estimate, a data-constrained reconstruction of the evolving ocean and sea ice state (Fukumori et al. 2021). Of particular relevance to modeling the Beaufort Gyre system, Arctic Ocean simulations in Coupled Model Intercomparison Project (CMIP6) models indicate large biases in halocline structure and transport through Bering Strait (Shu et al. 2023); ongoing analyses are exploring this in context with new understanding of the physical drivers of the Pacific–Arctic connection.

Presentations and discussions also featured the biogeochemical changes that have accompanied the physical changes in the Beaufort Gyre region, with observed shifts in the ocean carbon cycle that are related to changing sea ice properties and freshwater (DeGrandpre et al. 2020; DeFrancesco and Guéguen 2021). In the Chukchi Sea, summer atmospheric carbon dioxide uptake has increased in recent decades as sea ice continues to decline and primary productivity increases (Ouyang et al. 2022). Biogeochemical changes also include ocean acidification in the Beaufort Gyre surface waters (Zhang et al. 2020), and marked decreases in dissolved oxygen, a consequence of both physical and biological implications of halocline warming (Arroyo et al. 2023).

Research challenges and open questions

Discussions and breakout groups highlighted that research outcomes will be most valuable when the Beaufort Gyre and margins are considered as an interconnected system, with approaches that integrate the physical, chemical, and biological aspects. A system approach includes considering how its changing components are linked from the coastlines to the continental shelves and deep basins, as well as to the pan-Arctic environment and beyond. Open questions relate to observing gaps in several key components of the system.

The shelf margins of the region remain critically under-sampled due to inaccessibility in winter, dynamic ice conditions which make mooring deployments and autonomous sensing (by ice buoys) challenging, and inaccessibility for geopolitical reasons. This lack of data affects proper accounting of important metrics for change, such as freshwater and heat totals, and limits capacity to resolve precise physical mechanisms and seasonality of shelf–basin exchange and water pathways to and from the interior Canada Basin.

Boundary layers at the atmosphere–ice–ocean interfaces, through which energy is input and dissipated, are other crucial components of the system; these turbulent and varying regions are challenging to characterize and remain notably undersampled. Attributing system change and understanding drivers and energy transfer is hindered by a lack of data for resolving and integrating atmospheric influences (momentum and heat) on the ice–ocean system via the atmospheric boundary layer, including how these vary spatially and evolve over a seasonal cycle. It is further unknown, for example, how wave–ice interactions are changing as the sea ice pack continues to decay. Buoyancy fluxes at atmosphere–ice–ocean interfaces are not sufficiently well quantified. The increased presence of leads and polynyas in wintertime suggests that buoyancy fluxes are changing, although the cumulative effect of this on modifying properties of the upper ocean is largely unknown. This is particularly true for the prominent polynya that occurs on the northeastern Chukchi Shelf, which could alter the structure of the interior halocline. Openings in the pack ice also play a role in the system biogeochemistry. For instance, they could lead to hotspots for primary productivity (with light availability and/or upwelled nutrients) and allow for gas equilibration between the ocean and atmosphere, thereby mediating carbon fluxes—although there are insufficient data to assess the significance.

The strength of the halocline stratification relates to almost every measure of the Beaufort Gyre system, including controlling vertical heat and nutrient fluxes from deeper ocean layers to the surface. The central parts of the Beaufort Gyre region are the most strongly stratified in the Arctic, and a major open question is whether the coming years and decades will see increasing or decreasing stratification. On one hand, increased sea ice melt and river runoff should lead to stronger stratification; on the other hand, increased wind-energy input to an ocean less buffered by sea ice could lead to weaker stratification. Projections are further complicated because Arctic Ocean stratification is not well represented in global climate models.

Momentum transfer in boundary layers between the atmosphere, ice, and ocean is related to the large-scale dynamics of the Beaufort Gyre system that affect freshwater and heat storage and release. It remains an open question as to how the gyre will respond to changes in wind forcing, and on what time scales it will equilibrate. The important role of ice cover in regulating gyre spinup raises the question of how the gyre will respond to seasonally ice-free conditions. A further unknown relates to the stability of the atmospheric Beaufort High, and how this large-scale wind pattern might change in the future. An additionally important gyre boundary is the seafloor; an open research question is determining the role of bottom friction and associated energy transfers from the largest to the smallest scales.

Ocean eddies were a recurring topic of discussion. In particular, there are unanswered questions with respect to the role of eddies in water exchanges between the shelves and interior, the influence of eddies on Beaufort Gyre circulation and equilibration, and biogeochemical signatures and influences of eddy activity (e.g., the role of eddy activity in carbon uptake). Finally, there was consensus that identifying water pathways and circulation in the region, including the surface layer as well as the Pacific and Atlantic water layers, is a critical observing and modeling challenge. There has been work in recent years on water pathways from the shelf regions into the gyre, but these remain poorly constrained. There has been even less work on exit pathways for water in the halocline, including the fate of the heat that is presently accumulating within the gyre. Understanding of the influences to the pan-Arctic and North Atlantic system of changing water mass pathways into and out of the Beaufort Gyre region is incomplete.

Recommendations for research approaches

Workshop discussions converged on the following recommendations.

Strengthen international collaborations. Coordinated national and international collaborations are needed for a system-wide approach, particularly with respect to the marginal regions of the Beaufort Gyre system that span Russian, Canadian, and U.S. territorial waters. International partnerships need to be fostered; the U.S. and Canada partnership under the BGOS/JOIS program has been effective, as have coordinated efforts to compile metadata from moorings deployed by a number of different nations in the region. Partnerships need to be strengthened with respect to research in international waters. The International Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean bans commercial fishing until at least 2037 over most of the Beaufort Gyre sector, which was motivated by the limited understanding of fish stocks in the region. Collecting and disseminating data on the region's marine biodiversity to inform policy needs to be an internationally coordinated priority.

Advance community-based monitoring. Community-based monitoring has significant potential and can provide year-round monitoring in coastal regions. This in turn can inform community members in decision making and provide data on the broader system that fills important gaps. One example would be community deployments of surface-ocean drifters in coastal and source regions (e.g., the Mackenzie River outflow) to track summertime pathways into the Beaufort Gyre; although drifters are often destroyed by ice as they progress offshore, they can be a compelling way to infer pathways and a captivating indicator of the interconnectedness of the coastal communities and the Beaufort Gyre system. Shore-based high-frequency radar stations operating from communities on the coast of Alaska also provide information on the time-varying surface-ocean circulation in these coastal regions. This could be expanded to the eastern Beaufort coast. Community monitoring of harmful algal blooms has recently been initiated in certain areas; with the warming ocean temperatures, such efforts will need to be expanded.

Apply a broad range of observational approaches. Where shelf regions are inaccessible because of political or environmental conditions, remote sensing has a particularly vital role. Satellite information on sea ice, sea surface height, sea surface temperature, salinity, and other properties can provide critical data needs. This requires field measurements, such those under the NASA Salinity and Stratification at the Sea Ice Edge (SASSIE) program in the Beaufort Gyre region, to assess and improve sea surface salinity inferences from satellites. Ocean sensing with fiber optic telecommunications cables on the seafloor has enormous potential in regions that are difficult to access, and further exploration is recommended. There is precedent for scientific study using a Beaufort Sea cable that is part of a telecommunications network, with the possibility to record sea ice deformations, Arctic storms, and whale migration patterns.

There was consensus on the significant value and potential of autonomous platforms to fill many of the data gaps described above. Drones could be employed to sample the boundary layer in shelf regions where consolidated ice prohibits icebreaker access, or to provide data in thin boundary layers that are otherwise susceptible to influence from the host ship. Established technology, such as the Autonomous Ocean Flux Buoy (AOFB) that quantifies processes controlling heat and salt fluxes just below the ice, can continue to provide essential boundary layer data in conjunction with emerging technology, such as Tethered Ocean Profilers capable of sampling temperature and salinity at the evolving ice–ocean interface. Ice-Tethered Profilers (ITPs) continue to be critical for autonomous year-round measurements of water-column structure, including stratification, with data available in real time. Argo floats are an emerging possibility with more open water areas. With the deployment of moored sound beacons for acoustic tracking, drifting RAFOS floats could provide an effective mechanism for observing circulation pathways in the region. A network of navigation beacons would also support glider observations, including gliders with biogeochemical sensors.

Acoustic sensing of the ocean through measurements of sound signal travel times (acoustic tomography) is another viable strategy for filling data gaps. Tomography can provide needed information on water-column stratification, velocity, and vorticity, and also information on the marine soundscape to understand ecosystems and sea ice dynamics. Acoustic high-frequency echo sounders could be used more widely to characterize water structure (e.g., stratified layers to infer mixing) and other features such as eddies. Seismic oceanography is another form of acoustic sensing which can also provide high horizontal and spatial resolution, sufficient to sample internal waves, eddies, and mixing.

A comprehensive characterization of water mass pathways, circulation, and dynamics requires dedicated mooring arrays on the shelf-slope regions at the southern and western boundaries, as well as sampling at the regional extremes of the gyre, particularly in the most poorly sampled regions to the east and north of the gyre. ITPs have provided valuable data from the latter regions when sea ice circulation patterns have been favorable. Ship-based process studies, including those with interdisciplinary sampling, remain essential for characterizing many aspects of the system. Ships are also needed to maintain deployments of the autonomous systems. It is critical that the United States expand its fleet of polar icebreakers capable of operating in these remote regions.

Design and implement a tracer release study. In this workshop, as in past Arctic Ocean workshops, there were discussions on the need for a field and modeling tracer release study to understand cross-shelf exchange, and across- and along-isopycnal mixing and stirring in the Beaufort Gyre region. A collaborative experiment would involve the release of a tracer on isopycnal surfaces with carefully chosen release sites and depths. The tracer sulfur hexafluoride has been used in past midlatitude experiments since it has a low detection limit, which means experiments have the potential to cover thousands of kilometers and span time scales of several years. The resulting tracer patch would then need extensive surveying and sampling at later times. While such an undertaking has the potential to provide unprecedented understanding of water mass pathways and energetics, sea ice could pose a significant obstacle to its success.

Initiate a model intercomparison project. There was agreement that a new round of coordinated international modeling efforts under an Arctic Ocean Model Intercomparison Project (AOMIP) would be timely. This would build on the AOMIP and Forum for Arctic Modeling and Observational Synthesis (FAMOS) programs from 2001 to 2018 (Proshutinsky et al. 2019). The goal would be to formulate experiments and sensitivity studies to shed light on particular processes and evaluate intermodel discrepancies with respect to stratification, Pacific Water pathways and heat content, and Atlantic Water circulation. The AOMIP should also involve a wider use of tools to study sensitivity, which might include adjoint models to assess model sensitivity to specific forcing parameters. Models require evaluation in context with observations, and, as such, the AOMIP project would need to be integrated with observational programs. Adjoint-sensitivity studies can additionally provide knowledge to optimize observation strategies. Further, a hierarchy of models should be included, for example to improve process understanding via idealized layered models initiated by observations, or Lagrangian analyses to investigate water pathways.

The outcomes of an AOMIP would be relevant to evaluating global climate models analyzed under the CMIPs for Intergovernmental Panel on Climate Change (IPCC) assessment reports. A broader AOMIP effort could lead to a Climate Process Team (CPT) that would bring together researchers from multiple institutions to apply knowledge gained from field experiments and process studies in the development of improved parameterizations in global climate models.

Attention to data management and dissemination. An expanding variety of observational sensing techniques and approaches, including community-based monitoring, necessitates dedication to data synthesis, management, and distribution. This will likely require additional data coordination and sharing efforts—for instance, the establishment of a comprehensive mooring database. The Interagency Arctic Research Policy Committee (IARPC) can play an important role in this, including facilitating working groups on relevant coordination efforts. Data synthesis also includes providing access to near-real-time data for assimilation, and the development of reanalysis products for model forcing and evaluation.

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