BAMS
Meeting Summary

Polar Fresh Water in a Changing Global Climate

Linking Arctic and Southern Ocean Processes

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NORP-SORP Workshop on Polar Fresh Water: Sources, Pathways and Impacts of Freshwater in Northern and Southern Polar Oceans and Seas (SPICE-UP)

What: Up to 60 participants at a time and more than twice as many registrants in total from 20 nations and across experience levels met to discuss the current status of research on freshwater in both polar regions, future directions, and synergies between the Arctic and Southern Ocean research communities

When: 19–21 September 2022

Where: Online

KEYWORDS: Ocean; Arctic; Sea ice; Southern Ocean; Freshwater; Snowmelt/icemelt

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After three days of comprehensive review presentations, productive discussions, and enthusiastic debate, the online Workshop on Polar Fresh Water: Sources, Pathways and Impacts of Freshwater in Northern and Southern Polar Oceans and Seas jointly organized by the Northern Oceans Region Panel (NORP) and the Southern Ocean Region Panel (SORP) of the Climate and Ocean Variability and Predictability and Change (CLIVAR), co-sponsored by Climate and Cryosphere (CliC) and the Scientific Committee on Antarctic Research (SCAR), concluded successfully on 21 September 2022. This workshop brought together scientists with expertise in processes of the northern and southern high-latitude oceans to review the role and evolution of polar freshwater (FW) and compare and contrast the two polar oceans. In the oceanographic context of the workshop FW includes both non-salty sources such as precipitation or meltwater and relative "fresh" water masses of low salinity.

We took the participants on a journey a bit out of their comfort zone to better understand FW influences in the polar oceans, from the coast to the global basins, and from the sea ice and snow cover to the deep ocean. The workshop's narrative was designed to trace FW from its sources in rivers, meltwater, glacial calving, sea ice export, precipitation, and advected salinity anomalies to its impacts on ocean stratification and circulation with their implications for the global climate system. We connected observationalists, modelers, remote sensing experts, and those carrying out data assimilation with the aim of providing a holistic overview of polar FW and its projected future evolution. Both regional and global ocean communities took part. Many experts from both Northern and Southern Hemispheres joined, with less representation from large-scale climate modelers, however. This emphasizes the need for a more concerted effort to enhance exchange between the "regional" experts and the Earth system modeling specialists to better represent polar processes that have global impacts in climate change simulations.

The workshop featured three keynotes, each with two speakers covering the greater region of the Arctic and the Southern Ocean. Seven topical discussion sessions consisting of small breakout rooms, three summary discussions, and a wrap-up were organized across time zones following the keynotes. The participants and organizers were energized by the exceptionally well-prepared keynote presentations—contrasting northern and southern perspectives—and engaged in wide-ranging discussions. More than 140 registrants from several continents were able to participate in this virtual workshop. To welcome colleagues from all places, the workshop organizers addressed the time zone challenge by offering discussion sessions at various times and recordings of the keynote and summary sessions. Results of the breakout discussions were collected in shared documents editable by every participant. The clear structure of the workshop also provided people with the option to selectively participate in sessions covering their favorite topic.

The achievements of this workshop can be summarized as

- sharing multidisciplinary knowledge among a large group of scientists, each with expertise in parts of the broad topic;
- enhancing networking within the community, in particular between hemispheres, and between modelers and observationalists;
- identifying gaps in knowledge and observations, discussing unresolved conceptual issues and model biases; and
- forming a basis for future collaboration and further events, such as a summer school.

Sources and sinks

Taking the ocean perspective, precipitation, runoff, and inflow of relatively low salinity waters and sea ice melt are sources, whereas evaporation and sea ice formation constitute a sink. In both hemispheres, the poleward atmospheric moisture transport is balanced by an equatorward oceanic transport of low-salinity waters (Wijffels et al. 1992; Tietäväinen and Vihma 2008). Sources and sinks are estimated locally from in situ flux measurements and on large scales from less well-constrained model simulations. Additional important tools are ocean tracers, inverse models, and state estimates, which are constrained by observations, atmospheric reanalyses, and remote sensing products (e.g., Solomon et al. 2021).

In the Arctic, the dominant FW sources are precipitation over the ocean and riverine runoff. Both are projected to increase in the future, with more rain and less snow (McCrystall et al. 2021). However, current estimates from reanalysis are uncertain (Winkelbauer et al. 2022). FW accumulated in the Pacific sector of the Arctic during the past 20 years due to anthropogenic forcing (Jahn and Laiho 2020), and mainly derived from rivers and the Bering Strait. FW fluxes through the oceanic gateways have been measured since about 2000, although sparse coverage, data gaps, and funding gaps are ubiquitous. Liquid FW fluxes to the subpolar North Atlantic are expected to increase as the Arctic excess FW drains, but observations do not show any long-term positive trends (Curry et al. 2014; Karpouzoglou et al. 2022). Arctic sea ice export has been decreasing in accordance with the diminishing sea ice storage (Sumata et al. 2022).

In the Southern Ocean, precipitation exceeds evaporation with both decreasing toward Antarctica. Atmospheric reanalyses suggest an overall increase in net precipitation over past decades (Bromwich et al. 2011; Nicolas and Bromwich 2011; Pauling et al. 2016)—an expected signal in a warming climate. FW input from melting ice shelves and icebergs have been contributing significantly along the coast with a few giant icebergs also exporting FW far offshore (Depoorter et al. 2013; Silva et al. 2006; Abernathey et al. 2016; Rackow et al. 2017). Satellite data suggest that iceberg discharge almost doubled since the early 1990s and is expected to increase in the future (The IMBIE Team 2018; Paolo et al. 2015; Greene et al. 2022).

The seasonal sea ice formation and melt redistributes FW vertically and laterally, exceeds the atmospheric flux at higher latitudes, and forms a salinity minimum around the sea ice edge (Haumann et al. 2016; Abernathey et al. 2016). While sea ice fluxes are expected to decline in the future (Lockwood et al. 2021), satellite estimates suggest that sea ice fluxes have increased over past decades (Haumann et al. 2016). A net export of FW as part of upper-ocean waters balances the net surface input (Talley 2008).

Polar FW sources and sinks differ between the hemispheres. The Arctic receives 10% of the global river runoff, whereas runoff is negligible in the Southern Ocean. Icebergs redistribute FW in the Southern Ocean, but are negligible in the Arctic. The Arctic connects to adjacent basins through confined gateways, whereas the Southern Ocean is unconstrained. Southern Ocean sea ice is more seasonal than in the Arctic (Haine and Martin 2017). Atmospheric modes of variability and teleconnections have differing impacts in both polar regions. Dynamical impacts on the ocean are similar in both hemispheres, but poorly understood; for example, how sea ice (and ice shelf) melt is modified by turbulent mixing, and how coastal currents determine the FW exchange with the open ocean.

A fundamental issue concerns whether "freshwater" is a well-defined and useful concept, due to the sensitivity to reference salinity (Schauer and Losch 2019), with various approaches on how to define it (e.g., Bacon et al. 2015). Workarounds exist, for example by using salt budgets, but are not yet uniformly adopted and leave gaps in the interpretation of fluxes. Similarly, sources and sinks, regions, and passages should be defined consistently. Chemical tracers, such as oxygen and neodymium isotopes, are a useful emerging tool to identify FW sources, track its redistribution, and close budgets. Recent efforts by the GEOTRACES community have been helpful (Charette et al. 2020), but further studies based on provenance tracers are needed, such as those based on oxygen and neodymium isotopes (e.g., Laukert et al. 2017, 2022; Huhn et al. 2021), to track glacial runoff (e.g., from Greenland) far offshore. Previous use of widely available tracers has been subject to significant caveats, e.g., nutrients in the Arctic (Forryan et al. 2019), therefore, more robust alternatives are needed.

General circulation models—from regional ocean to global coupled climate models—provide unambiguous FW sources, sinks and closed budgets, but suffer from uncertainties and shortcomings. First, there is a large spread in simulated precipitation and runoff associated with an interactive atmosphere. Second, models typically do not resolve processes on small scales that disperse and transport FW. Third, ice shelf and iceberg processes are not well represented in models. Satellite data, state estimates, and process studies using observations from drift campaigns help to evaluate model simulations of FW sources, sinks, and budgets, and resolve the seasonal cycle.

Change in ocean structure and circulation

Following keynote presentations and discussions on sources and sinks of FW, we turned our attention to how this FW affects the ocean. In the Arctic, the majority of the FW is stored in the Amerasian Basin, in response to the anticyclonic, convergent Beaufort Gyre circulation (Haine et al. 2015; Carmack et al. 2016). Over recent decades, increased sea ice melt and river runoff in this region have caused surface freshening and a more stable stratification in the water column (Macdonald et al. 1999; McPhee et al. 2009; Toole et al. 2010; Peralta-Ferriz and Woodgate 2015). Models struggle to simulate the observed stratification in the Amerasian Basin and do not capture the increased stratification nor surface freshening of the recent decades (Holloway et al. 2007; Wang et al. 2022; Muilwijk et al. 2023), which is linked to unrealistically deep vertical mixing (Rosenblum et al. 2021). This likely has similar reasons as the excessive deep convection in the Southern Ocean (Heuzé et al. 2015) and questions the capability of model parameterizations controlling stratification.

Improved understanding of "change" in ocean structure and circulation is needed to understand dynamical processes caused by the addition of FW over a range of temporal scales. A primary focus has been the impact on the stratification of the water column; sea ice and meteoric water input at the surface is often reported to strengthen the vertical stratification of the water column (Timmermans and Marshall 2020). However, the addition of glacial meltwater at depth from ice shelves has been shown to result in immediate turbulent mixing at the ice shelf front (Naveira Garabato et al. 2017) but also persistent meltwater signatures up to 500 km from the ice shelf (Biddle et al. 2017; Nakayama et al. 2019). This indicates a sub–mixed layer stratification in the water column. The buoyancy changes associated with FW fluxes have been shown to drive instabilities at submesoscales, further impacting heat fluxes to sea ice and ice shelves (Timmermans et al. 2012; Giddy et al. 2021). Due to their small time and space scales, observations and modeling of submesoscale processes near and under sea ice are limited and represent a new scientific frontier.

The discussion highlighted uncertainties in projections of FW change and its impact on stratification and circulation in the Arctic Ocean. It was emphasized that the nonuniform geographic domain used for FW computations in the Arctic leads to ambiguous results (e.g., Tsubouchi et al. 2018). The currently predominant haline stratification in the polar regions is predicted to persist until the end of this century, except in the Barents Sea and parts of the marginal ice zone of the Southern Ocean (Muilwijk et al. 2023). Stratification projections are sensitive to small model errors in surface buoyancy fluxes, such as brine rejection during sea ice formation, and the formulation of vertical mixing schemes (Zhang and Steele 2007; Nguyen et al. 2009). Narrow coastal and slope currents impact the vertical redistribution and transport of FW (Carmack et al. 2016), but their representation in global ocean models with coarse resolution is problematic. The same goes for ocean dynamics affecting FW input by ice shelves, tidewater glaciers, and rivers, particularly in cases where the FW does not enter at the surface. On the other hand, large-scale currents, such as the Transpolar Drift Stream, require improved satellite-observations (e.g., Doglioni et al. 2022) and numerical modeling to accurately represent the cross-basin near-surface transport.

Although the discussion focused on the ocean, we emphasized the importance of the atmosphere as a major driver of ocean dynamics. Atmospheric circulation strongly influences not only the upper-ocean liquid freshwater distribution by currents but also mixing and shelf water mass transformation (e.g., Luneva et al. 2020). Particularly in the Arctic, retreating sea ice will affect atmosphere–ocean fluxes and momentum transfer across the ocean and ice surfaces (Martin et al. 2014; Meneghello et al. 2018).

The potential benefit of future drift campaigns to understand FW-relevant processes and help to evaluate model simulations at a local level and on seasonal time scales was highlighted in both discussions of sources and sinks as well as ocean circulation. Past examples include MOSAiC (Shupe et al. 2022; Nicolaus et al. 2022; Rabe et al. 2022), N-ICE (Granskog et al. 2018), ISW (e.g., Gordon and Lukin 1992), and ISPOL (Hellmer et al. 2008); a year-round effort is direly needed in the south.

Global linkages

In both hemispheres, polar FW impacts deep and intermediate water formation due to changes in stratification, with ramifications for global climate. While the impact of Arctic FW is confined to the subpolar North Atlantic, Southern Ocean FW has circumpolar effects. Model projections suggest that in both hemispheres FW inputs will increase where they have the most impact on intermediate or deep water formation (e.g., Meijers 2014; Zanowski et al. 2021).

In the north, Fram Strait FW fluxes may have greater potential to affect North Atlantic deep convection (Schulze Chretien and Frajka-Williams 2018; de Steur et al. 2018;

LeBras et al. 2021) than Arctic FW exports west of Greenland, which remain within the Labrador Current (Schulze Chretien and Frajka-Williams 2018). FW from the Labrador current can have a delayed impact on deep convection either by wind anomalies forcing a transport out of the Labrador current into the subpolar gyre or by recirculating with the latter (Holliday et al. 2020; Biló et al. 2022; Fox et al. 2022). How and where FW-induced deep water formation changes affect the Atlantic meridional overturning circulation (AMOC) is a question under active investigation. Specifically, the Overturning in the Subpolar North Atlantic Program (OSNAP) measurements show that Labrador Sea waters contribute only a small percentage of the AMOC variability on subdecadal time scales (Lozier et al. 2019). High-resolution modeling studies demonstrated no significant impact by enhanced Greenland runoff on open-ocean deep convection in the Labrador Sea and suggest that such convection contributes minimally to the long-term mean AMOC strength, whereas Arctic overflow waters are potentially more important (Böning et al. 2016; Zhang and Thomas 2021).

In the Southern Hemisphere, Antarctic FW governs upper-ocean stratification south of the Polar Front (Stewart and Haine 2016), affecting global climate via several pathways. Precipitation and glacial FW regulate the oceanic heat supply to the Antarctic Ice Sheet by affecting coastal stratification (Thompson et al. 2018). In continental shelf sectors (e.g., Amundsen and Bellingshausen) with a large FW input and weak easterly winds, warm offshore Circumpolar Deep Water can reach ice shelves, leading to strong melting. In continental shelf sectors where sea ice is formed, a local FW deficit results in the densification of shelf waters, ultimately forming Antarctic Bottom Water (Silvano et al. 2018; Morrison et al. 2020; Solodoch et al. 2022). Moreover, upper-ocean stratification in the open Southern Ocean, chiefly established by sea ice melt (Abernathey et al. 2016), exerts a profound control on the large-scale structure and circulation of the Southern Hemisphere oceans. One aspect of this is the generation of the permanent pycnocline in the seasonal sea ice zone (Klocker et al. 2023), setting apart relatively well-ventilated upper-ocean waters from poorly ventilated deep waters, and thereby configuring ocean interior ventilation (DeVries et al. 2017).

As with sources and sinks, the discussion highlighted the growing potential to track the redistribution of FW from different sources by noble gas, isotope and radionuclide concentrations (Rhein et al. 2018).

Models are useful tools to fill gaps in observations and help to gain an overall understanding of the role of polar FW. This includes tracking of simulated FW to identify export routes as well as projections of the global feedbacks between ice, ocean and atmosphere triggered by large-scale polar freshening. Model uncertainty due to shortcomings in, among others, (sub)mesoscale dynamics in the boundary current, mixing processes, local wind forcing, location of water mass formation, and dense overflows were extensively discussed. For simulating ice shelf melting, meltwater export and mixing processes more accurate bathymetry data are urgently needed, which is an ongoing effort (Dorschel et al. 2022; GEBCO Seabed 2030 Project, https://seabed2030.org). Improved process understanding in particular in the Southern Ocean is needed and so are in situ observations supporting this process.

Robust impacts, such as Southern Hemisphere surface cooling, sea ice expansion, deep ocean warming, reduced bottom water production, and (sub)tropical precipitation shifts occurring over decades to centuries, have been identified (Bronselaer et al. 2018; Park and Latif 2019). Part of the discussion was also dedicated to the role of internal climate variability largely masking potentially already ongoing change (Jahn and Laiho 2020).

Model uncertainty still is a major liability in our capability to project future uptake of anthropogenic heat and carbon by the ocean. Extensive, year-round observational programs in high-latitudes planned jointly with the modeling community are much needed to overcome these problems.

Conclusions

This workshop yielded an excellent overview of the current state of research on the sources, pathways, and impacts of FW in the Arctic and the Southern Oceans, as well as cross-hemispheric linkages, similarities, and common challenges. The keynote talks highlighted the need for more observations as well as for improving climate models, which was further elaborated during the discussions sessions. While enhanced polar FW export is anticipated to affect our climate over the coming decades to centuries, (sub)mesoscale processes and the seasonal cycle were identified as major gaps in our knowledge, observations and modeling capabilities. Participants unanimously praised the bipolar exchange, which triggered interest in intensifying such activity in a summer school and creating new opportunities for future north–south collaborations.

Last, the online format including coordination across global time zones worked better than expected and provided an inclusive platform for scientific exchange. Summary slides and a brief logistics report of the workshop are provided by CLIVAR (2023).

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