Polar Fresh Water in a Changing Global Climate: Linking Arctic and Southern Ocean Processes

Benjamin Rabe[1], Torge Martin[2], Amy Solomon[3], Karen M. Assmann[4], Louise C. Biddle[5], Thomas Haine[6], Tore Hattermann[7], F. Alexander Haumann[8,1,9], Alexandra Jahn[10], Theodoros Karpouzoglou[7], Georgi Laukert[2,11,12], Alberto Naveira Garabato[13], Erica Rosenblum[14], Elisabeth Sikes[15], Liping Yin[16,17], Xiangdong Zhang[18,19]

[1] Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany

[2] GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

[3] Cooperative Institute for Research in Environmental Sciences, University of Colorado and National Oceanic and Atmospheric Administration Physical Sciences Laboratory, Boulder, CO, USA

[4] Institute of Marine Research, Tromsø, Norway

[5] Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden

[6] The Johns Hopkins University, Baltimore, MD, USA

[7] Norwegian Polar Institute, Tromsø, Norway

[8] Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA

[9] Ludwig Maximilian University Munich, Munich, Germany

[10] Department of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO, USA

[11] Department of Oceanography, Dalhousie University, Halifax, NS, Canada

[12] Woods Hole Oceanographic Institution, Woods Hole, MA, USA

[13] Ocean and Earth Science, University of Southampton, Southampton, UK

[14] Centre for Earth Observation Science, University of Manitoba, Winnipeg, MB, Canada

[15]Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA

[16] First Institute of Oceanography, Qingdao, China

[17] International CLIVAR Project Office, Qingdao, China

Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-23-0046.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

[18] Department of Atmospheric Sciences and International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA
[19] National Oceanic and Atmospheric Administration Cooperative Institute for Satellite Earth System Studies, North Carolina State University, Asheville, NC, USA

Corresponding authors: Benjamin Rabe (benjamin.rabe@awi.de), Torge Martin (tomartin@geomar.de)

Information Box

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 FW in both polar regions, future directions and synergies between the Arctic and Southern Ocean research communities
WHERE: online with plenary keynote and summary sessions and several breakout discussions
WHEN: September 19–21, 2022; varying times to accommodate different time zones

After three days of comprehensive review presentations, productive discussions, and enthusiastic debate, the online workshop on polar fresh water: **S**ources, **P**athways and **I**mpa**C**ts of fr**E**shwater in northern and so**U**thern **P**olar oceans and seas (SPICE-UP) 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 fresh water (FW) and compare and contrast the two polar oceans. In the oceanographic context of the

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

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:

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

- 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;
- 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

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

(Curry et al, 2015; 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.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

A fundamental issue concerns whether “fresh water” 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 to 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; Laukert et al., 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 anti-cyclonic, 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;

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

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 melt water 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 sub-mesoscales, 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 non-uniform 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

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

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 includeMOSAiC (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 et al., 2014; Zanowski et al. 2021).

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

In the north, Fram Strait FW fluxes may have greater potential to affect North Atlantic deep convection (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 (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 sub-decadal 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

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

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

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

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 bi-polar exchange, which triggered interest in intensifying such activity in a summer school and creating new opportunities for future north-south collaborations.

Lastly, 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).

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Acknowledgements

We thank the following co-sponsors for support: World Climate Research Programme (WCRP), World Meteorological Organization (WMO), Climate and Ocean: Variability, Predictability, and Change (CLIVAR), Climate and Cryosphere (CliC), Scientific Committee on Antarctic Research (SCAR), Global Ocean Observing System (GOOS), and Global Climate Observing System (GCOS). The zoom license was provided by our co-sponsor International Arctic Science Committee (IASC). We acknowledge support by the Open Access Publication Funds of Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung.

References

Abernathey, R. P., I. Cerovecki, P. R. Holland, E. Newsom, M. Mazloff, and L. D. Talley, 2016: Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geosci*, **9**, 596–601, https://doi.org/10.1038/ngeo2749.

Bacon, S., Y. Aksenov, S. Fawcett, and G. Madec, 2015: Arctic mass, freshwater and heat fluxes: methods and modelled seasonal variability. *Phil. Trans. R. Soc. A.*, **373**, 20140169, https://doi.org/10.1098/rsta.2014.0169.

Biddle, L. C., K. J. Heywood, J. Kaiser, and A. Jenkins, 2017: Glacial Meltwater Identification in the Amundsen Sea. *Journal of Physical Oceanography*, **47**, 933–954, https://doi.org/10.1175/JPO-D-16-0221.1.

Biló, T. C., F. Straneo, J. Holte, and I. A. - A. Le Bras, 2022: Arrival of New Great Salinity Anomaly Weakens Convection in the Irminger Sea. *Geophysical Research Letters*, **49**, https://doi.org/10.1029/2022GL098857.

Böning, C. W., E. Behrens, A. Biastoch, K. Getzlaff, and J. L. Bamber, 2016: Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geosci*, **9**, 523–527, https://doi.org/10.1038/ngeo2740.

Bromwich, D. H., J. P. Nicolas, and A. J. Monaghan, 2011: An Assessment of Precipitation Changes over Antarctica and the Southern Ocean since 1989 in

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Contemporary Global Reanalyses*. *Journal of Climate*, **24**, 4189–4209, https://doi.org/10.1175/2011JCLI4074.1.

Bronselaer, B., M. Winton, S. M. Griffies, W. J. Hurlin, K. B. Rodgers, O. V. Sergienko, R. J. Stouffer, and J. L. Russell, 2018: Change in future climate due to Antarctic meltwater. *Nature*, **564**, 53–58, https://doi.org/10.1038/s41586-018-0712-z.

Carmack, E. C., and Coauthors, 2016: Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. *J. Geophys. Res. Biogeosci.*, **121**, 675–717, https://doi.org/10.1002/2015JG003140.

Charette, M. A., and Coauthors, 2020: The Transpolar Drift as a Source of Riverine and Shelf- Derived Trace Elements to the Central Arctic Ocean. *JGR Oceans*, **125**, https://doi.org/10.1029/2019JC015920.

CLIVAR, 2023: Final Report on the NORP-SORP workshop on polar fresh water: Sources, Pathways and ImpaCts of frEsh water in northern and soUthern Polar oceans and seas (SPICE UP). CLIVAR Report No. 02/2023, https://doi.org/10.36071/clivar.rp.2.2023 .

Curry, B., C. M. Lee, B. Petrie, R. E. Moritz, and R. Kwok, 2014: Multiyear Volume, Liquid Freshwater, and Sea Ice Transports through Davis Strait, 2004-10*. *JOURNAL OF PHYSICAL OCEANOGRAPHY*, **44**, 1244–1266, https://doi.org/10.1175/JPO-D-13-0177.1.

Depoorter, M. A., J. L. Bamber, J. A. Griggs, J. T. M. Lenaerts, S. R. M. Ligtenberg, M. R. van den Broeke, and G. Moholdt, 2013: Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature*, **502**, 89–92, https://doi.org/10.1038/nature12567.

DeVries, T., M. Holzer, and F. Primeau, 2017: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature*, **542**, 215–218, https://doi.org/10.1038/nature21068.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Doglioni, F., R. Ricker, B. Rabe, A. Barth, C. Troupin, and T. Kanzow, 2022: *Sea surface height anomaly and geostrophic current velocity from altimetry measurements over the Arctic Ocean (2011–2020)*. Physical oceanography,.

Dorschel, B., and Coauthors, 2022: The International Bathymetric Chart of the Southern Ocean Version 2. *Sci Data*, **9**, 275, https://doi.org/10.1038/s41597-022-01366-7.

Forryan, A., S. Bacon, T. Tsubouchi, S. Torres-Valdés, and A. C. Naveira Garabato, 2019: Arctic freshwater fluxes: sources, tracer budgets and inconsistencies. *The Cryosphere*, **13**, 2111–2131, https://doi.org/10.5194/tc-13-2111-2019.

Fox, A. D., and Coauthors, 2022: Exceptional freshening and cooling in the eastern subpolar North Atlantic caused by reduced Labrador Sea surface heat loss. *Ocean Sci.*, **18**, 1507–1533, https://doi.org/10.5194/os-18-1507-2022.

Giddy, I., S. Swart, M. du Plessis, A. F. Thompson, and S. - A. Nicholson, 2021: Stirring of Sea- Ice Meltwater Enhances Submesoscale Fronts in the Southern Ocean. *J. Geophys. Res. Oceans*, **126**, https://doi.org/10.1029/2020JC016814.

Gordon, A. L., and V. Lukin, 1992: Ice Station Weddell #1. *Antarctic Journal of the United States*, **XVII**, 97–99.

Granskog, M. A., I. Fer, A. Rinke, and H. Steen, 2018: Atmosphere-Ice-Ocean-Ecosystem Processes in a Thinner Arctic Sea Ice Regime: The Norwegian Young Sea ICE (N-ICE2015) Expedition. *J. Geophys. Res. Oceans*, **123**, 1586–1594, https://doi.org/10.1002/2017JC013328.

Greene, C. A., A. S. Gardner, N.-J. Schlegel, and A. D. Fraser, 2022: Antarctic calving loss rivals ice-shelf thinning. *Nature*, **609**, 948–953, https://doi.org/10.1038/s41586-022-05037-w.

Haine, T. W. N., and T. Martin, 2017: The Arctic-Subarctic sea ice system is entering a seasonal regime: Implications for future Arctic amplification. *Sci Rep*, **7**, 4618, https://doi.org/10.1038/s41598-017-04573-0.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Haine, T. W. N., and Coauthors, 2015: Arctic freshwater export: Status, mechanisms, and prospects. *Global and Planetary Change*, **125**, 13–35, https://doi.org/10.1016/j.gloplacha.2014.11.013.

Haumann, F. A., N. Gruber, M. Münnich, I. Frenger, and S. Kern, 2016: Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature*, **537**, 89–92, https://doi.org/10.1038/nature19101.

Hellmer, H. H., M. Schröder, C. Haas, G. S. Dieckmann, and M. Spindler, 2008: The ISPOL drift experiment. *Deep Sea Research Part II: Topical Studies in Oceanography*, **55**, 913–917, https://doi.org/10.1016/j.dsr2.2008.01.001.

Heuzé, C., J. K. Ridley, D. Calvert, D. P. Stevens, and K. J. Heywood, 2015: Increasing vertical mixing to reduce Southern Ocean deep convection in NEMO3.4. *Geosci. Model Dev.*, **8**, 3119–3130, https://doi.org/10.5194/gmd-8-3119-2015.

Holliday, N. P., and Coauthors, 2020: Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nat Commun*, **11**, 585, https://doi.org/10.1038/s41467-020-14474-y.

Holloway, G., and Coauthors, 2007: Water properties and circulation in Arctic Ocean models. *J. Geophys. Res.*, **112**, C04S03, https://doi.org/10.1029/2006JC003642.

Huhn, O., M. Rhein, T. Kanzow, J. Schaffer, and J. Sültenfuß, 2021: Submarine Meltwater From Nioghalvfjerdsbræ (79 North Glacier), Northeast Greenland. *J. Geophys. Res. Oceans*, **126**, https://doi.org/10.1029/2021JC017224.

Jahn, A., and R. Laiho, 2020: Forced Changes in the Arctic Freshwater Budget Emerge in the Early 21st Century. *Geophys. Res. Lett.*, **47**, https://doi.org/10.1029/2020GL088854.

Karpouzoglou, T., L. de Steur, L. H. Smedsrud, and H. Sumata, 2022: Observed Changes in the Arctic Freshwater Outflow in Fram Strait. *JGR Oceans*, **127**, https://doi.org/10.1029/2021JC018122.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Klocker, A., A. Naveira Garabato, F. Roquet, C. de Lavergne, and S. Rintoul, 2022: *Generation of the Southern Ocean pycnocline by sea ice-ocean interactions*. Oceanography,.

Laukert, G., and Coauthors, 2017: Ocean circulation and freshwater pathways in the Arctic Mediterranean based on a combined Nd isotope, REE and oxygen isotope section across Fram Strait. *Geochimica et Cosmochimica Acta*, **202**, 285–309, https://doi.org/10.1016/j.gca.2016.12.028.

Laukert, G., I. Peeken, D. Bauch, T. Krumpen, E. C. Hathorne, K. Werner, M. Gutjahr, and M. Frank, 2022: Neodymium isotopes trace marine provenance of Arctic sea ice. *Geochem. Persp. Let.*, **22**, 10–15, https://doi.org/10.7185/geochemlet.2220.

Le Bras, I., F. Straneo, M. Muilwijk, L. H. Smedsrud, F. Li, M. S. Lozier, and N. P. Holliday, 2021: How Much Arctic Fresh Water Participates in the Subpolar Overturning Circulation? *JOURNAL OF PHYSICAL OCEANOGRAPHY*, **51**, 955–973, https://doi.org/10.1175/JPO-D-20-0240.1.

Lockwood, J. W., C. O. Dufour, S. M. Griffies, and M. Winton, 2021: On the Role of the Antarctic Slope Front on the Occurrence of the Weddell Sea Polynya under Climate Change. *Journal of Climate*, **34**, 2529–2548, https://doi.org/10.1175/JCLI-D-20-0069.1.

Lozier, M. S., and Coauthors, 2019: A sea change in our view of overturning in the subpolar North Atlantic. *Science*, **363**, 516–521, https://doi.org/10.1126/science.aau6592.

Luneva, M. V., V. V. Ivanov, F. Tuzov, Y. Aksenov, J. D. Harle, S. Kelly, and J. T. Holt, 2020: Hotspots of Dense Water Cascading in the Arctic Ocean: Implications for the Pacific Water Pathways. *J. Geophys. Res. Oceans*, **125**, https://doi.org/10.1029/2020JC016044.

Macdonald, R. W., E. C. Carmack, F. A. McLaughlin, K. K. Falkner, and J. H. Swift, 1999: Connections among ice, runoff and atmospheric forcing in the Beaufort

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Gyre. *Geophys. Res. Lett.*, **26**, 2223–2226, https://doi.org/10.1029/1999GL900508.

Martin, T., M. Steele, and J. Zhang, 2014: Seasonality and long-term trend of Arctic Ocean surface stress in a model. *J. Geophys. Res. Oceans*, **119**, 1723–1738, https://doi.org/10.1002/2013JC009425.

McCrystall, M. R., J. Stroeve, M. Serreze, B. C. Forbes, and J. A. Screen, 2021: New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nat Commun*, **12**, 6765, https://doi.org/10.1038/s41467-021-27031-y.

McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire, 2009: Rapid change in freshwater content of the Arctic Ocean. *Geophys. Res. Lett.*, **36**, L10602, https://doi.org/10.1029/2009GL037525.

Meijers, A. J. S., 2014: The Southern Ocean in the Coupled Model Intercomparison Project phase 5. *Phil. Trans. R. Soc. A.*, **372**, 20130296, https://doi.org/10.1098/rsta.2013.0296.

Meneghello, G., J. Marshall, J. Campin, E. Doddridge, and M. Timmermans, 2018: The Ice- Ocean Governor: Ice- Ocean Stress Feedback Limits Beaufort Gyre Spin- Up. *Geophysical Research Letters*, **45**, https://doi.org/10.1029/2018GL080171.

Morrison, A. K., A. McC. Hogg, M. H. England, and P. Spence, 2020: Warm Circumpolar Deep Water transport toward Antarctica driven by local dense water export in canyons. *Sci. Adv.*, **6**, eaav2516, https://doi.org/10.1126/sciadv.aav2516.

Muilwijk, M., A. Nummelin, C. Heuzé, I. V. Polyakov, H. Zanowski, and L. H. Smedsrud, 2023: Divergence in Climate Model Projections of Future Arctic Atlantification. *Journal of Climate*, **36**, 1727–1748, https://doi.org/10.1175/JCLI-D-22-0349.1.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Naveira Garabato, A. C. and Coauthors, 2017: Vigorous lateral export of the meltwater outflow from beneath an Antarctic ice shelf. *Nature*, **542**, 219–222, https://doi.org/10.1038/nature20825.

Nguyen, A. T., D. Menemenlis, and R. Kwok, 2009: Improved modeling of the Arctic halocline with a subgrid-scale brine rejection parameterization. *J. Geophys. Res.*, **114**, C11014, https://doi.org/10.1029/2008JC005121.

Nicolas, J. P., and D. H. Bromwich, 2011: Precipitation Changes in High Southern Latitudes from Global Reanalyses: A Cautionary Tale. *Surv Geophys*, **32**, 475–494, https://doi.org/10.1007/s10712-011-9114-6.

Nicolaus, M., and Coauthors, 2022: Overview of the MOSAiC expedition: Snow and sea ice. *Elementa: Science of the Anthropocene*, **10**, 000046, https://doi.org/10.1525/elementa.2021.000046.

Paolo, F. S., H. A. Fricker, and L. Padman, 2015: Volume loss from Antarctic ice shelves is accelerating. *Science*, **348**, 327–331, https://doi.org/10.1126/science.aaa0940.

Park, W., and M. Latif, 2019: Ensemble global warming simulations with idealized Antarctic meltwater input. *Clim Dyn*, **52**, 3223–3239, https://doi.org/10.1007/s00382-018-4319-8.

Pauling, A. G., C. M. Bitz, I. J. Smith, and P. J. Langhorne, 2016: The Response of the Southern Ocean and Antarctic Sea Ice to Freshwater from Ice Shelves in an Earth System Model. *Journal of Climate*, **29**, 1655–1672, https://doi.org/10.1175/JCLI-D-15-0501.1.

Peralta-Ferriz, C., and R. A. Woodgate, 2015: Seasonal and interannual variability of pan-Arctic surface mixed layer properties from 1979 to 2012 from hydrographic data, and the dominance of stratification for multiyear mixed layer depth shoaling. *Progress in Oceanography*, **134**, 19–53, https://doi.org/10.1016/j.pocean.2014.12.005.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Rabe, B., and Coauthors, 2022: Overview of the MOSAiC expedition: Physical oceanography. *Elementa: Science of the Anthropocene*, **10**, 00062, https://doi.org/10.1525/elementa.2021.00062.

Rackow, T., C. Wesche, R. Timmermann, H. H. Hellmer, S. Juricke, and T. Jung, 2017: A simulation of small to giant Antarctic iceberg evolution: Differential impact on climatology estimates: MELT AND DRIFT OF SMALL TO GIANT ICEBERGS. *J. Geophys. Res. Oceans*, **122**, 3170–3190, https://doi.org/10.1002/2016JC012513.

Rhein, M., R. Steinfeldt, O. Huhn, J. Sültenfuß, and T. Breckenfelder, 2018: Greenland Submarine Melt Water Observed in the Labrador and Irminger Sea. *Geophysical Research Letters*, **45**, https://doi.org/10.1029/2018GL079110.

Rosenblum, E., R. Fajber, J. C. Stroeve, S. T. Gille, L. B. Tremblay, and E. C. Carmack, 2021: Surface Salinity Under Transitioning Ice Cover in the Canada Basin: Climate Model Biases Linked to Vertical Distribution of Fresh Water. *Geophysical Research Letters*, **48**, https://doi.org/10.1029/2021GL094739.

Schauer, U., and M. Losch, 2019: "Freshwater" in the Ocean is Not a Useful Parameter in Climate Research. *Journal of Physical Oceanography*, **49**, 2309–2321, https://doi.org/10.1175/JPO-D-19-0102.1.

Schulze Chretien, L. M., and E. Frajka-Williams, 2018: Wind-driven transport of fresh shelf water into the upper 30 m of the Labrador Sea. *Ocean Sci.*, **14**, 1247–1264, https://doi.org/10.5194/os-14-1247-2018.

Shupe, M. D., and Coauthors, 2022: Overview of the MOSAiC expedition: Atmosphere. *Elementa: Science of the Anthropocene*, **10**, 00060, https://doi.org/10.1525/elementa.2021.00060.

Silva, T. A. M., G. R. Bigg, and K. W. Nicholls, 2006: Contribution of giant icebergs to the Southern Ocean freshwater flux. *J. Geophys. Res.*, **111**, C03004, https://doi.org/10.1029/2004JC002843.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Silvano, A., S. R. Rintoul, B. Peña-Molino, W. R. Hobbs, E. van Wijk, S. Aoki, T. Tamura, and G. D. Williams, 2018: Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Sci. Adv.*, **4**, eaap9467, https://doi.org/10.1126/sciadv.aap9467.

Solodoch, A., A. L. Stewart, A. McC. Hogg, A. K. Morrison, A. E. Kiss, A. F. Thompson, S. G. Purkey, and L. Cimoli, 2022: How Does Antarctic Bottom Water Cross the Southern Ocean? *Geophysical Research Letters*, **49**, https://doi.org/10.1029/2021GL097211.

Solomon, A., and Coauthors, 2021: Freshwater in the Arctic Ocean 2010–2019. *Ocean Sci.*, **17**, 1081–1102, https://doi.org/10.5194/os-17-1081-2021.

Steur, L., C. Peralta- Ferriz, and O. Pavlova, 2018: Freshwater Export in the East Greenland Current Freshens the North Atlantic. *Geophys. Res. Lett.*, **45**, https://doi.org/10.1029/2018GL080207.

Stewart, K. D., and T. W. N. Haine, 2016: Thermobaricity in the Transition Zones between Alpha and Beta Oceans. *Journal of Physical Oceanography*, **46**, 1805–1821, https://doi.org/10.1175/JPO-D-16-0017.1.

Sumata, H., L. de Steur, S. Gerland, D. V. Divine, and O. Pavlova, 2022: Unprecedented decline of Arctic sea ice outflow in 2018. *Nat Commun*, **13**, 1747, https://doi.org/10.1038/s41467-022-29470-7.

Talley, L. D., 2008: Freshwater transport estimates and the global overturning circulation: Shallow, deep and throughflow components. *Progress in Oceanography*, **78**, 257–303, https://doi.org/10.1016/j.pocean.2008.05.001.

The IMBIE team, 2018: Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, **558**, 219–222, https://doi.org/10.1038/s41586-018-0179-y.

Thompson, A. F., A. L. Stewart, P. Spence, and K. J. Heywood, 2018: The Antarctic Slope Current in a Changing Climate. *Rev. Geophys.*, **56**, 741–770, https://doi.org/10.1029/2018RG000624.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Tietäväinen, H., and T. Vihma, 2008: Atmospheric moisture budget over Antarctica and the Southern Ocean based on the ERA-40 reanalysis. *Int. J. Climatol.*, **28**, 1977–1995, https://doi.org/10.1002/joc.1684.

Timmermans, M., and J. Marshall, 2020: Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate. *J. Geophys. Res. Oceans*, **125**, https://doi.org/10.1029/2018JC014378.

Timmermans, M.-L., S. Cole, and J. Toole, 2012: Horizontal Density Structure and Restratification of the Arctic Ocean Surface Layer. *JOURNAL OF PHYSICAL OCEANOGRAPHY*, **42**, 659–668, https://doi.org/10.1175/JPO-D-11-0125.1.

Toole, J. M., M. - L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky, and J. A. Richter- Menge, 2010: Influences of the ocean surface mixed layer and thermohaline stratification on Arctic Sea ice in the central Canada Basin. *J. Geophys. Res.*, **115**, 2009JC005660, https://doi.org/10.1029/2009JC005660.

Tsubouchi, T., and Coauthors, 2018: The Arctic Ocean Seasonal Cycles of Heat and Freshwater Fluxes: Observation-Based Inverse Estimates. *Journal of Physical Oceanography*, **48**, 2029–2055, https://doi.org/10.1175/JPO-D-17-0239.1.

Wang, S., Q. Wang, M. Wang, G. Lohmann, and F. Qiao, 2022: Arctic Ocean Freshwater in CMIP6 Coupled Models. *Earth's Future*, **10**, https://doi.org/10.1029/2022EF002878.

Wijffels, S. E., R. W. Schmitt, H. L. Bryden, and A. Stigebrandt, 1992: Transport of Freshwater by the Oceans. *J. Phys. Oceanogr.*, **22**, 155–162, https://doi.org/10.1175/1520-0485(1992)022<0155:TOFBTO>2.0.CO;2.

Winkelbauer, S., M. Mayer, V. Seitner, E. Zsoter, H. Zuo, and L. Haimberger, 2022: Diagnostic evaluation of river discharge into the Arctic Ocean and its impact on oceanic volume transports. *Hydrol. Earth Syst. Sci.*, **26**, 279–304, https://doi.org/10.5194/hess-26-279-2022.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.

Zanowski, H., A. Jahn, and M. M. Holland, 2021: Arctic Ocean Freshwater in CMIP6 Ensembles: Declining Sea Ice, Increasing Ocean Storage and Export. *J. Geophys. Res. Oceans*, **126**, https://doi.org/10.1029/2020JC016930.

Zhang, J., and M. Steele, 2007: Effect of vertical mixing on the Atlantic Water layer circulation in the Arctic Ocean. *J. Geophys. Res.*, **112**, C04S04, https://doi.org/10.1029/2006JC003732.

Zhang, R., and M. Thomas, 2021: Horizontal circulation across density surfaces contributes substantially to the long-term mean northern Atlantic Meridional Overturning Circulation. *Commun Earth Environ*, **2**, 112, https://doi.org/10.1038/s43247-021-00182-y.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0046.1.