

Article submitted to journal

Subject Areas:

Physical oceanography, climate dynamics, anthropogenic change

Keywords:

Arctic Ocean freshwater, sub-polar North Atlantic Ocean, Atlantic meridional overturning circulation

Author for correspondence:

Thomas Haine

e-mail: Thomas.Haine@jhu.edu

Arctic freshwater impact on the Atlantic Meridional Overturning Circulation: Status and prospects

Thomas W. N. Haine, Ali H. Siddiqui, and Wenrui Jiang

Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD, USA

Arguably, the most conspicuous evidence for anthropogenic climate change lies in the Arctic Ocean. For example, the summer-time Arctic sea ice extent has declined over the last 40 years and the Arctic Ocean freshwater storage has increased over the last 30 years. Coupled climate models project that this extra freshwater will pass Greenland to enter the sub-polar North Atlantic Ocean (SPNA) in the coming decades. Coupled climate models also project that the Atlantic Meridional Overturning Circulation (AMOC) will weaken in the 21st century, associated with SPNA buoyancy increases. Yet, it remains unclear when the Arctic anthropogenic freshening signal will be detected in the SPNA, or what form the signal will take. Therefore, this paper reviews and synthesizes the state of knowledge on Arctic Ocean and SPNA salinity variations and their causes. The paper focuses on the export processes in data-constrained ocean circulation model hindcasts. One challenge is to quantify and understand the relative importance of different competing processes. The paper also discusses the prospects to detect the emergence of Arctic anthropogenic freshening and the likely impacts on the AMOC. For this issue, the challenge is to distinguish anthropogenic signals from natural variability.

1. Introduction

An essential challenge in physical oceanography and climate dynamics concerns the influence of polar low-salinity seawater on the global ocean circulation. At low latitudes the ocean loses water to the atmosphere because evaporation exceeds precipitation. The atmosphere

carries this water polewards where it accumulates in the surface ocean and thereby decreases salinity. This low-salinity seawater (“freshwater” in the parlance of the field) is carried equatorwards by the ocean circulation, which replenishes the low-latitude ocean and completes the cycle. The equatorwards flow of freshwater affects the circulation itself, however, because the low-salinity water has low density and therefore inhibits vertical exchange [Stommel, 1961].

These processes occur prominently in the sub-polar North Atlantic Ocean (SPNA), where low-salinity outflow from the Arctic Ocean impinges on regions of strong vertical exchange. This strong vertical exchange forms a branch of the Atlantic Meridional Overturning Circulation (AMOC), which plays a leading role in North Atlantic and northern hemisphere climate (for example, see Srokosz et al. 2021, Zhang et al. 2019 and references therein).

Research in the last 30–40 years has established that this system is changing. The system fluctuates spontaneously over years and decades and it changes in response to exogenous (anthropogenic) climate forcing. Specifically, extensive sustained efforts to observe and model Arctic Ocean processes have revealed large, interannual, near-surface Arctic freshwater anomalies. These anomalies appear to have natural origins, with anthropogenic decadal trends superimposed (these issues are discussed below in section 2). It is also known that, historically, freshwater from the Arctic propagates to the SPNA as a continuous stream with large anomalies. Furthermore, coupled climate models project that this Arctic Ocean freshwater export to the SPNA will increase in the 21st century. Extensive, sustained efforts to observe and model SPNA processes have also revealed large, interannual, near-surface SPNA salinity (freshwater) anomalies. These anomalies appear to have natural origins, with no clear role for anthropogenic forcing (section 3). Observed anomalies in the AMOC also appear to be natural (section 4). Moreover, coupled climate models project that the AMOC will weaken in the 21st century. Yet it is unclear when, and in what way, the Arctic anthropogenic freshening signal will be detected in the SPNA (section 5) and how it will impact the SPNA stratification and circulation, and the AMOC (section 6).

This paper reviews and synthesizes the literature on these issues. The specific goals are to characterize the historical Arctic Ocean and SPNA salinity variations and discuss their mechanisms. The approach is empirical and quantitative. The approach is synthetic, in the sense that it tries to summarize the state of knowledge and speculate about future prospects. It also focuses on basin-scales (from 100s to 1000s of km) and long periods (from years to decades). The paper focuses on how the Arctic Ocean affects the SPNA, and hence the AMOC, not the other way round. It also focuses on oceanic processes, not atmospheric or coupled ocean/atmosphere processes. The paper concludes by articulating the present gaps in understanding on how Arctic freshwater impacts the SPNA and the AMOC, and on the causes of AMOC fluctuations. A strategy to close these gaps is outlined.

Although the paper is mainly a review and synthesis, some new analyses are presented from a dynamical state estimate from an ocean circulation model (ECCOv4r4; see Methods section (a)) and from a gridded data synthesis (EN4; see Methods section (b)). The new results confirm, extend, and synthesize the results from published papers. They allow us to construct a coherent synthesis of the impact of historical Arctic freshwater anomalies on the SPNA, at least in ECCOv4r4. Such a view does not exist in the published literature. In turn, this ECCOv4r4 synthesis motivates the open questions and recommendations in the final section 6.

2. Arctic Ocean freshwater variations and mechanisms

Observations show freshwater accumulating in the Arctic Ocean in the last few decades [Solomon et al., 2021]. The first reliable estimate of the liquid freshwater content (LFC) of the Arctic Ocean was $97,000\text{km}^3$ [Aagaard and Carmack, 1989]. (LFC is the integrated, normalized salinity anomaly relative to a reference salinity of, in this case, $S_{ref} = 34.8\text{g/kg}$). Several studies have updated this value to quantify the freshwater accumulation over time. For example, Rabe et al. [2014] estimate an extra $12,000\text{km}^3$ over 1992–2012. Haine et al. [2015] estimate an extra $5,300\text{km}^3$

for 2000–2010 relative to 1980–2000. And Proshutinsky et al. [2019] estimate an extra 6,400km³ of liquid freshwater between 2003 and 2018 in the Beaufort Gyre, which is the largest Arctic freshwater reservoir. This buildup of liquid freshwater is seen in Fig. 1 (Liquid Storage panel), which shows observations of liquid freshwater volume increasing (red line; see Haine 2020 and Haine et al. [2015] for full discussion and details on the data sources; and see Wang et al. 2023 for a recent update). Fig. 1 reveals the sources of the extra liquid freshwater too: they are reduced sea ice (Solid Storage panel), increased runoff, and increased inflow through Bering Strait (left hand panels). The observed outflows (right hand panels) are unchanged or increasing in magnitude (Liquid Fram Strait panel; recent observations of Fram Strait liquid freshwater flux show no overall increase Karpouzoglou et al. 2022). They do not match the increased inflows, however, causing the freshwater accumulation in the Arctic Ocean.

Fig. 1 also shows results from the Community Earth System Model (CESM) version 1.1 based on Jahn and Laiho [2020]. The CESM is a fully coupled, state-of-the-art global Earth system model [Hurrell et al., 2013]. The model results comprise an ensemble of historical control simulations (gray) and two ensembles of 21st century projections (the large ensemble in purple and low warming scenario in green; see Jahn and Laiho 2020, Kay et al. 2015, and Sanderson et al. 2017 for details). Using the amplitude of the control ensemble variability (horizontal lines) allows to determine when the anthropogenic-forced signals emerge (vertical purple and green lines; see Jahn and Laiho 2020 for details). The anthropogenic decline in Arctic sea ice emerged first, in the 2000s (Solid Storage panel; IPCC 2021, Notz and Marotzke 2012). The anthropogenic increase in Arctic liquid freshwater emerged next, in the 2010s (Liquid Storage panel). None of the inflow or outflow fluxes in Fig. 1 show emergence of an anthropogenic signal yet. The CESM results suggest that anthropogenic effects will increase the freshwater flux through Davis Strait, however, with a signal emerging in the 2020s. The Fram Strait fluxes are projected to change too, with less solid (sea ice) flux, more liquid flux (and more total flux), but the anthropogenic-forced signal is not expected to emerge for 15–40 years.

The CESM results match the observations in Fig. 1 reasonably well, although the CESM liquid Fram Strait freshwater flux is too small. In recent follow-up studies, Zanowski et al. [2021] and Weijer et al. [2022] show that other Coupled Model Intercomparison Project 6th phase (CMIP6) coupled climate models do not have this bias. Still, more work is needed to characterize the fingerprint of anthropogenic perturbation to the Arctic freshwater cycle in the coming decades. The projected increase in atmospheric moisture flux convergence is moderately well established [Ford and Frauenfeld, 2022, McCrystall et al., 2021, Stadnyk et al., 2021, Vihma et al., 2016], but the anticipated changes to the marine outflows are poorly known. Moreover, well-known, stubborn biases exist in the Arctic Oceans of CMIP6 models [Heuzé et al., 2023, Khosravi et al., 2022, Muilwijk et al., 2023, Shu et al., 2023, Wang et al., 2023].

This evidence focuses on the **kinematic** inflows and outflows of freshwater to the Arctic (meaning they do not involve circulation changes). But **dynamical mechanisms** (involving circulation changes) are also important, especially for the Beaufort Gyre. Proshutinsky et al. [2019] summarize three main factors controlling the freshwater buildup in the Beaufort Gyre:

- (i) Ekman pumping from anticyclonic winds, which accumulates freshwater from around the gyre, including runoff from the shelves, and deepens the halocline [Johnson et al., 2018, Manucharyan et al., 2016, Proshutinsky et al., 2002, Stewart and Haine, 2013].
- (ii) Ice melt and growth, which limits the gyre spin-up. This “Ice-Ocean Governor” feedback mechanism emphasizes the role of sea ice in controlling geostrophic currents [Meneghello et al., 2018]. Specifically, the surface ocean stress depends on the difference between the sea ice velocity and the surface ocean velocity. Therefore, stress on the ocean can change, hence changing Ekman pumping and freshwater accumulation, by changing sea ice conditions with fixed winds (see also Giles et al. 2012 and Martin et al. 2014).

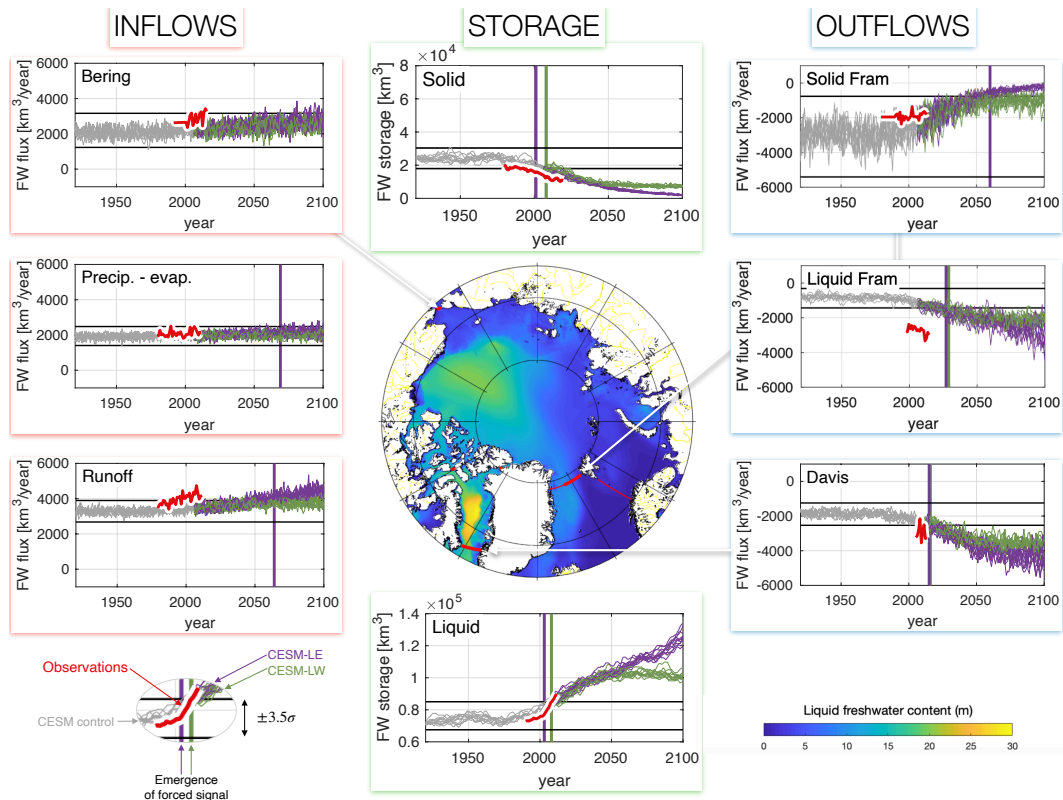


Figure 1. Observations (in red) and climate model projections of the Arctic Ocean freshwater cycle. The left (right) subplots show the principal time series of freshwater (FW) inflows (outflows; $\text{km}^3\text{yr}^{-1}$, relative to $S_{ref} = 34.8\text{g/kg}$; positive freshens the Arctic Ocean). The middle subplots show the freshwater volume stored in the Arctic Ocean as sea ice (solid, top) and liquid (bottom) freshwater (km^3 relative to 34.8g/kg). Results from the CESM historical control (gray), large ensemble (LE, purple), and low warming (LW, green) experiments are shown (from [Jahn and Laiho 2020](#)). The subplots show when the forced, anthropogenic signal emerges (the time of first permanent departure from the $\pm 3.5\sigma$ envelope of control variability, where σ is the standard deviation; horizontal and vertical lines). The basemap shows the liquid freshwater content, which is the vertically-integrated salinity anomaly relative to 34.8g/kg . Adapted from [Haine \[2020\]](#).

- (iii) Stratification and mixing changes along continental slopes, which deepens the halocline and lengthens the gyre spin-up time [[Manucharyan and Isachsen, 2019](#), [Manucharyan and Spall, 2016](#)].

In particular, the Beaufort Gyre circulation has strengthened (become more anticyclonic) and expanded as the liquid freshwater has accumulated over the last 30 years [[Fukumori et al., 2021a](#)]. This strengthening is associated with stronger sea level air pressure (SLP) over the western Arctic [[Proshutinsky and Johnson, 1997](#)]. Weak Beaufort Gyre circulation events (and weak sea SLP) have also occurred, however, for example in 1989 [[Haine et al., 2015](#)]. Modulating the Beaufort Gyre strength by varying the western Arctic wind field (i.e., SLP) triggers large flushing of Arctic freshwater to the SPNA both east and west of Greenland, at least in model experiments [[Stewart and Haine, 2013](#), [Zhang et al., 2021](#)]. Therefore, concern exists that the Arctic Ocean is primed to release freshwater to the SPNA, either in flushing events or as a steadily freshening stream.

In summary: Observations show freshwater accumulating in the Arctic Ocean in the last few decades. Coupled climate models attribute this freshwater accumulation to anthropogenic forcing. Although understanding of the mechanisms responsible for the accumulation is

incomplete, evidence suggests that a shift in Arctic Ocean winds could trigger a flushing of this freshwater into the North Atlantic.

3. Sub-polar North Atlantic freshwater variations and mechanisms

Observations show large-scale freshening events in the SPNA on decadal time scales. For example, Fig. 2 shows the liquid freshwater content for the SPNA since 1950 from hydrographic climatologies and the ECCOv4r3 dynamically-consistent state estimate (see Methods section (a)). The liquid freshwater content estimates broadly agree and show decade-long freshening events starting around 1965, 1980, and 2010. These events have been called “Great Salinity Anomalies” (GSAs) [Belkin, 2004, Belkin et al., 1998, Biló et al., 2022, Dickson et al., 1988]. They involve changes in liquid freshwater content of around $10,000\text{km}^3$, which is similar to the changes seen in the Arctic freshwater reservoirs in Fig. 1. GSAs appear to be a natural mode of Arctic/Atlantic Ocean variability that have occurred for at least the last century [Dooley et al., 1984, Sundby and Drinkwater, 2007, Zhang and Vallis, 2006]

Fig. 2 also shows the average salinity in the upper 200m in the eastern SPNA over the last 30 years (see the purple boxes in Fig. 3 for the definition of the region). The data come from the EN4 observational climatology (Methods section (b)) and the ECCOv4r4 state estimate. Again, the data and state estimate broadly agree at interannual periods. The increase in liquid freshwater content for the whole SPNA centered on 2012 appears in the upper 200m eastern SPNA as a shift from a salty anomaly in 2008 to a fresh anomaly in 2016 with a salinity change of around 0.2g/kg . Indeed, Holliday et al. [2020] call 2014–2017 the largest freshening event in the eastern SPNA in the last 120 years.

The cause(s) of the 2016 fresh event (and of the 2008 saline event) are elucidated by the salinity and sea level observations in Fig. 3. The red sea level contours show the North Atlantic Current (NAC) path in the SPNA for the two years prior to the salinity anomalies (i.e., 2006–2007 and 2014–2015). Specifically, compare the red contours in the purple boxes in Fig. 3 for each period. In the two years prior to the 2008 saline anomaly the NAC extended further to the west, shrinking the sub-polar gyre and allowing saline subtropical water to enter the eastern SPNA. In the two years prior to the 2016 fresh anomaly the NAC extended further to the east, expanding the sub-polar gyre and allowing fresh sub-polar water to enter the eastern SPNA. In other words, the upstream routing of saline subtropical or fresh sub-polar water determines the eastern SPNA salinity anomalies. The processes controlling eastern SPNA temperature anomalies are consistent: 2008 was a warm event, whereas 2016 was a cool event [Piecuch et al., 2017, Tesdal and Haine, 2020].

This argument is an example of a proximate mechanism to modulate the salinity in the eastern SPNA. Several ultimate causes for the salinity anomalies have been proposed in the literature. They include:

- (i) The export of freshwater from the Arctic as sea ice and liquid freshwater via the Fram and Davis Straits to the western SPNA [Sundby and Drinkwater, 2007, Zhang et al., 2021]. The fresh anomalies then propagate to the eastern SPNA in the NAC. For example, Holliday et al. [2020] explain the 2016 fresh event as the rerouting of the Arctic-sourced Labrador Current water in the upper 200m into the northern branch of the NAC.
- (ii) Relatedly, saline events are attributed to anomalous salt transport from the subtropical gyre via the NAC [Holliday, 2003, Häkkinen et al., 2011, Tesdal and Haine, 2020, Thierry et al., 2008, Yeager et al., 2012, Zhang and Vallis, 2006].
- (iii) Air/sea interaction in the SPNA. For example, Josey and Marsh [2005] argue that the freshening from 1960–2000 can be largely explained by changes in the air-sea freshwater exchange, mainly increased precipitation.

A natural and revealing complement to the Eulerian analyses in Figs. 2 and 3 is a Lagrangian perspective. A Lagrangian perspective emphasizes the complicated transport pathways that exist

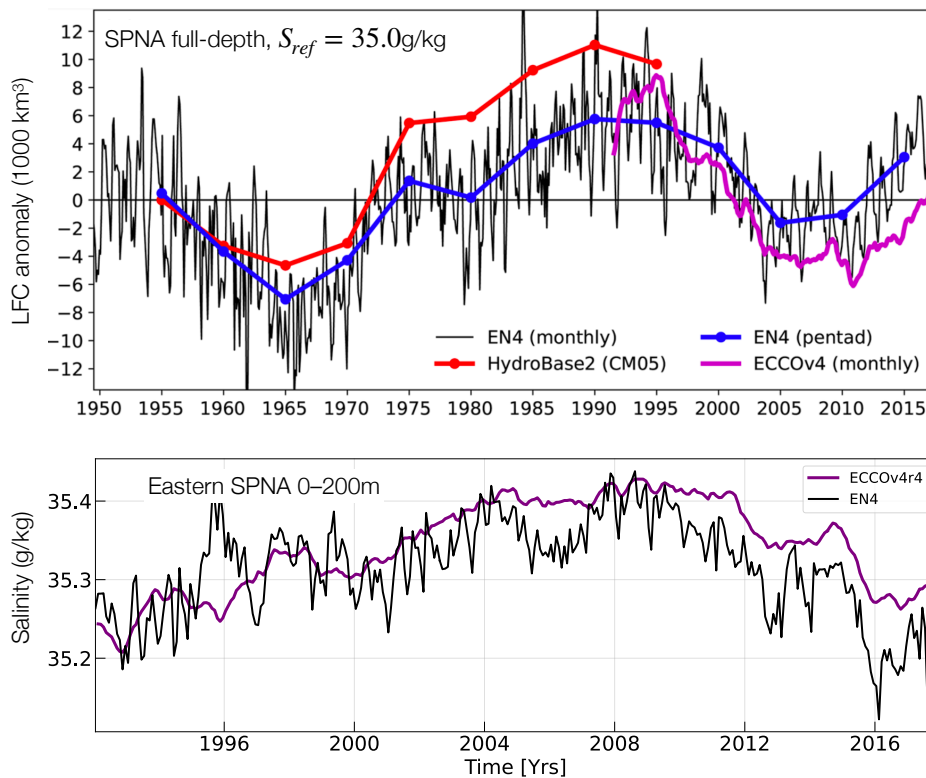


Figure 2. Diagnostics of sub-polar North Atlantic (SPNA) salinity variations. Upper: Liquid freshwater content (LFC) anomaly relative to $S_{ref} = 35.0\text{g/kg}$ for the SPNA. Data are from the EN4 climatology (monthly and five-year mean; Good et al. 2013), the HydroBase2 climatology [Curry and Mauritzen, 2005], and ECCOV4r3. Adapted from Tesdal and Haine [2020]. Lower: Average salinity for the upper 200m of the eastern SPNA from the EN4 climatology, and the ECCOV4r4 state estimate (Methods section (a)). See Fig. 3 for the definition of the eastern SPNA region.

in reality, but that are hidden in the Eulerian LFC, salinity, and sea level timeseries in Figs. 2 and 3. To this end, we show in Fig. 4 new results of three-dimensional backtracking Lagrangian particles in the ECCOV4r4 state estimate (see also Asbjørnsen et al. 2021, Desbruyères et al. 2021, Fox et al. 2022, Koul et al. 2020). Particles are released from the eastern SPNA (upper 200m) in 2008 and 2016 and integrated backwards for 16 years (Methods section (c)). The particles are colored according to their source region 16 years before release. In both events, the regions that feed the eastern SPNA 16 years later are (in decreasing order of importance): the subtropical and tropical North Atlantic, the SPNA, the Arctic Ocean or the Canadian Arctic Archipelago (CAA), and the Nordic Seas. Most of the Arctic particles reach the SPNA via the transpolar drift and the CAA (west of Greenland) rather than via the Nordic Seas. Few particles reach the SPNA from the Beaufort Gyre over 16 years. The differences between the 2008 and 2016 events are as follows: There are 17% more particles from the SPNA in the 2016 event (meaning an increase from 27.0% of all particles to 31.5% of all particles, see Fig. 4, which is a 17% increase). There are 7% fewer from the subtropics, and 27% more from the Arctic (9% more come from the Arctic, CAA, and Nordic Seas combined).

In other words, before the 2016 fresh event: water resided longer in the SPNA being freshened by air/sea interaction, less saline water came from the subtropics, and more freshwater came from the Arctic. These results are consistent with all of the mechanisms identified above.

Some potential mechanisms are considered to be less important. One example is anthropogenic loss of the Greenland Ice Sheet (GIS), which has not yet led to detectable SPNA freshening

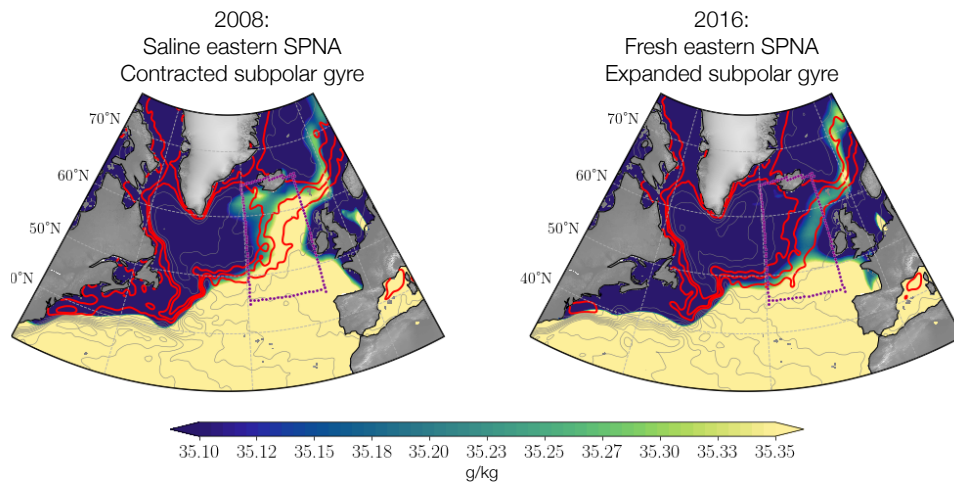


Figure 3. Variations in eastern SPNA salinity modulated by the NAC. Colors show annual-average surface salinity [from EN4; Good et al., 2013] for 2008 (2016), which correspond to saline (fresh) years in the eastern SPNA (purple box). Contours show the average sea level (absolute dynamic topography from AVISO) for the preceding two years (2006–2007 and 2014–2015), which correspond to contracted and expanded sub-polar gyre states. The contours are from -0.8 to 0.8 m with a spacing of 0.1 m and are smoothed with a 400 km Gaussian filter. The NAC follows the red contours (-0.3 , -0.2 , and -0.1 m) in the central North Atlantic. Adapted from Weijer et al. [2022].

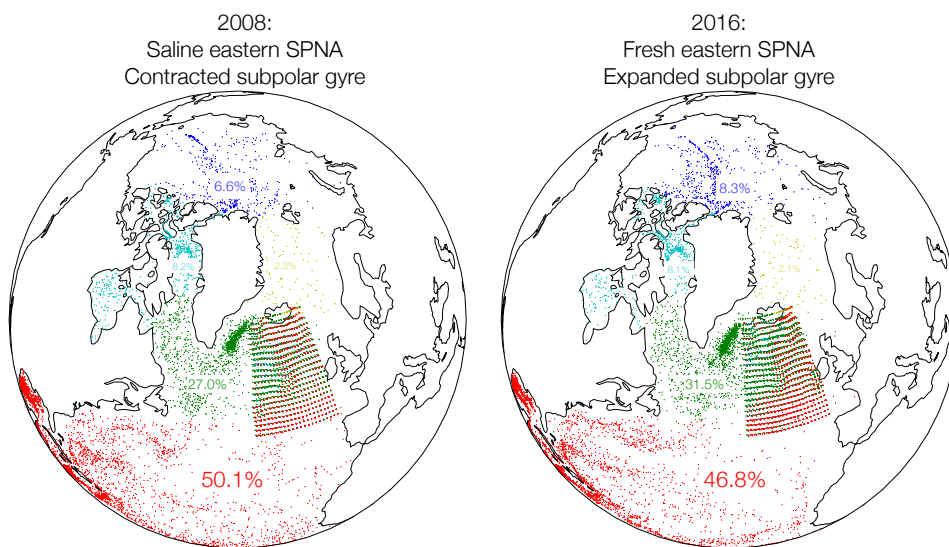


Figure 4. Three-dimensional Lagrangian particle origins in the ECCOv4r4 state estimate. The 7744 particles are released in the eastern SPNA on the grid of red dots over the upper 200 m in (left) 2008 and (right) 2016 when the eastern SPNA was saline (fresh) and the sub-polar gyre was contracted (expanded). The particles are backtracked for 16 years and colored according to their starting region. The percentages show the fractions of the released particles from each starting region.

[Böning et al., 2016, Stolzenberger et al., 2022]. Nevertheless, uncertainty exists on the fate of GIS meltwater because it depends on circulation model resolution and how the GIS discharge is

parametrized [Marson et al., 2021, Schulz et al., 2022, Stolzenberger et al., 2022]. These processes are not accurately represented in the ECCOv4r4 state estimate.

Finally, other studies emphasize **dynamical mechanisms** controlling eastern SPNA salinity. Wind and buoyancy fluctuations influence the circulation, especially on interannual and decadal timescales, respectively [Biaostoch et al., 2008, Jackson et al., 2022, Kostov et al., 2021, Yeager and Danabasoglu, 2014]. For example, when the North Atlantic Oscillation (NAO) is positive, anomalous mid-latitude westerly winds drive an expanded sub-polar gyre and fresh anomalies in the eastern SPNA, as in 2016 (Fig. 3; Weijer et al. 2022). Conversely, when the NAO is negative, the sub-polar gyre contracts and saline anomalies occupy the eastern SPNA, as in 2008.

In summary: Observations show decadal, upper-ocean, propagating salinity variations in the SPNA since 1950. The salinity variations involve shifts in the NAC and expansion/contraction of the sub-polar gyre in the eastern SPNA. Understanding of the ultimate causes of the salinity variations is incomplete. Nevertheless, the leading candidate mechanisms are: changes in salt transport from the subtropics and the Arctic, changes in the AMOC, and changes in SPNA precipitation. These mechanisms are typically associated with changes in SPNA winds, especially the NAO.

4. Sub-polar North Atlantic AMOC variations

The AMOC has also been implicated in SPNA salinity anomalies. Observations show the SPNA AMOC fluctuates on interannual to decadal periods. For example, it strengthened between 1980 and the mid 1990s, then weakened to the 2010s, and is now possibly strengthening again [Desbruyères et al., 2019, Jackson et al., 2022]. These variations are attributed to atmospheric forcing, especially the winter NAO [Biaostoch et al., 2008, Yeager and Danabasoglu, 2014]. The variations broadly coincide with the fluctuations seen in Figs. 2 and 3. Indeed, Bryden et al. [2020] estimate that the eastern SPNA freshening from 2008–2016 is consistent with the weakening of the 26°N AMOC freshwater flux to the SPNA from 2009–2016. Robson et al. [2016] found support for this idea in a coupled climate model.

Other studies emphasize the importance of the horizontal gyre circulation, instead of the AMOC, in controlling interannual to decadal SPNA variations. For example, Piecuch et al. [2017] find in ECCOv4r3 that horizontal gyre circulation anomalies across the southern boundary of the SPNA mainly determine 1992–2015 SPNA heat content anomalies. Tesdal and Haine [2020] reach the same conclusion for SPNA LFC anomalies. Both these studies consider anomalies for the entire, full-depth SPNA, however, integrating from the sea-surface to the sea-floor. How this picture depends on different choices of control volume is unclear, however. For example, the salinity changes in the upper 200m of the eastern SPNA seen in Fig. 2 may depend less on anomalies inherited from the subtropics (either from horizontal gyre circulation or AMOC changes). Moreover, Holliday et al. [2018] use transbasin SPNA hydrographic sections to show that high heat flux associates with high AMOC strength, whereas high freshwater flux associates with high gyre circulation. Reconciling these divergent viewpoints is an important challenge.

Looking ahead to 2100, the AMOC is projected to decline in almost all coupled climate models as a result of anthropogenic forcing [Cheng et al., 2013, Weijer et al., 2020].¹ Moreover, the AMOC may weaken irreversibly, meaning that the circulation system crosses a threshold (or tipping point) that leads to a non-linear, abrupt slowdown [Weijer et al., 2019]. This possibility is deemed to have low likelihood [IPCC, 2021, Lohmann and Ditlevsen, 2021], but the impacts on humankind would be large [Armstrong McKay et al., 2022, Lenton et al., 2019]. Despite the possibility of such forced signals, the observed AMOC variations mentioned above are probably natural [Fu et al., 2020, Latif et al., 2022]. In other words, the anthropogenic forced AMOC signal has not yet emerged from the noise of natural variability.

¹It is worth noting that some paleoclimate proxy data have been used to infer that the AMOC has weakened since the 1800s [Caesar et al., 2021]. The claim is disputed, however [Kilbourne et al., 2022], and a more complete analysis of proxy records is ambivalent on weakening [Moffa-Sánchez et al., 2019].

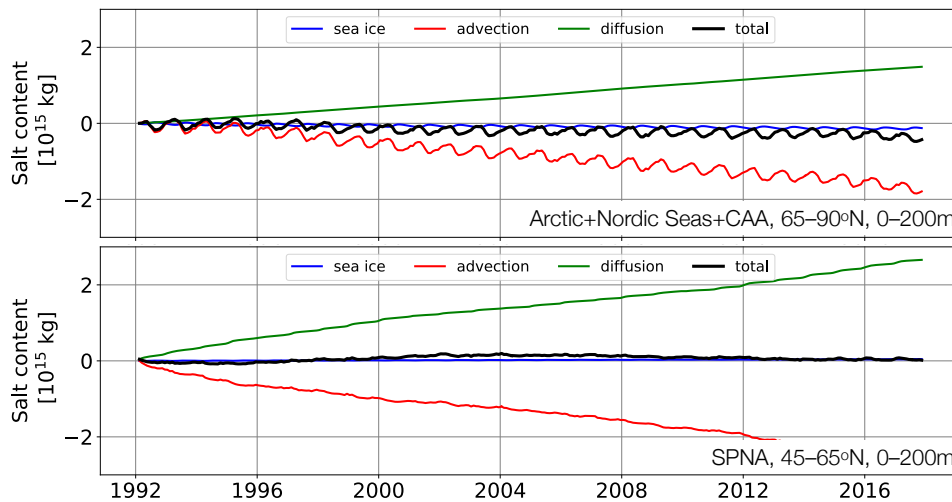


Figure 5. Decomposition of volume-integrated salt mass for the (upper) Arctic (north of 65°N) and (lower) SPNA (45–65°N) upper 200m from the ECCOv4r4 state estimate. The cumulative (time-integrated) contributions to the total salt mass change due to advection, diffusion, and sea ice are shown. For details on how each term is defined, see Methods section (d).

In summary: Variations in both the AMOC and the horizontal gyre circulation have been implicated in SPNA salinity variations, based on evidence from both observations and models. Yet, inconsistencies remain, for example, to do with the importance of different circulation changes for different aspects of SPNA salinity. Although coupled climate models project AMOC weakening in the 21st century under anthropogenic climate change, the SPNA changes seen to date are probably natural.

5. Arctic/sub-polar North Atlantic salt exchanges

Another useful perspective on the impact of Arctic freshwater export on the AMOC is the net exchange of salt between the Arctic and SPNA. Therefore, we examine this exchange in Fig. 5 using new results from ECCOv4r4 for 1992–2017. The SPNA is defined as the region between 45 and 65°N and the Arctic is defined as north of 65°N (i.e., it includes the Nordic Seas and CAA). In both cases, only the upper 200m of the water column is included. Fig. 5 shows the cumulative (time-integrated) contribution of various processes to the change in the total mass of salt in these reservoirs (see Methods section (d)). These processes are: advection across the faces of the reservoir, diffusion across the faces, and exchange with sea ice due to melting and freezing (sea ice has a salinity around 4g/kg). Note that there is no air/sea exchange of salt.

For the Arctic, Nordic Seas, and CAA, Fig. 5 shows that diffusion increases the salt content (because the water deeper than 200m is salty). Advection decreases the salt content (because the seawater outflow exceeds the seawater inflow by the water flux received from the atmosphere and land). Sea ice exchange also decreases the salt content (because, overall, the region exports salt in sea ice). Salt exchanges due to advection and sea ice have seasonal cycles. The effect on the total salt content is a decreasing trend over 1992–2017, which is due to an overall imbalance between sea ice, advection, and diffusion.² The total loss is about 0.35×10^{15} kg. This salt mass corresponds to an increase of about $10,000\text{km}^3$ of liquid freshwater relative to $S_{ref} = 34.8\text{g/kg}$

²One might ask which term is responsible for the overall decrease in Arctic, Nordic Seas and CAA salt content in Fig. 5. But the linear trends indicate that the individual salt fluxes are constant over 1992–2017. Therefore, the net salt loss cannot be attributed to any one of them: the fluxes simply sum to a constant negative value that indicates salt loss.

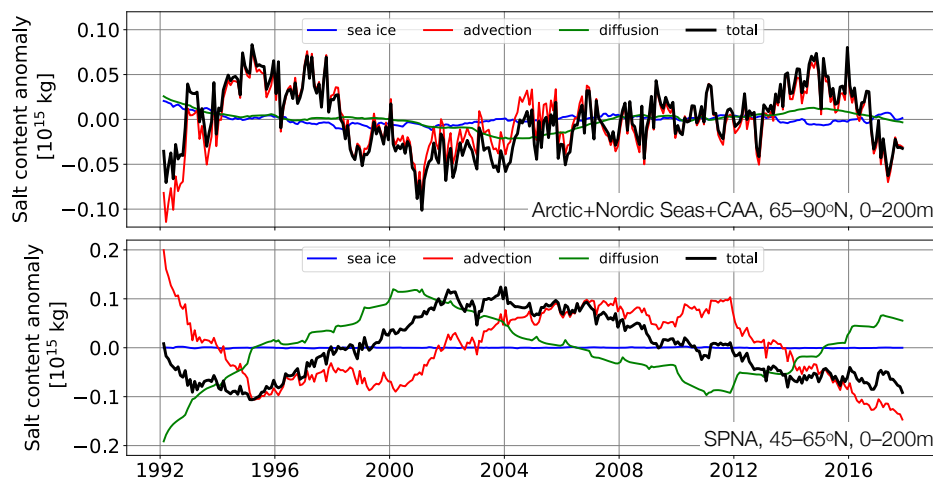


Figure 6. As Fig. 5, except salt content anomalies are shown after removing linear trends. Note the y -axes differ between the two panels.

(assuming, reasonably, that the reservoir volume is constant). Thus, it is broadly consistent with the LFC increase discussed in section 2.

For the SPNA, Fig. 5 shows that diffusion increases salt content and advection decreases it; again, the main salt balance is between these two terms. Sea ice is a weak factor for the SPNA and no long-term trend is visible for the total salt content in Fig. 5.

Interannual variations in the total salt content exist for both the Arctic and, especially, the SPNA in Fig. 5. These variations are shown in detail in Fig. 6, which shows the same timeseries with linear trends removed. For the Arctic, Nordic Seas, and CAA, the variations have a magnitude of around 10^{14} kg (corresponding to LFC variations of around 3000km^3). These variations are closely associated with variations in advection. For the SPNA, the variations have a similar magnitude, but they are associated with variations in both advection and diffusion. Salt content anomalies due to diffusion lead those due to advection, at least for the single fresh-to-salty-to-fresh cycle in ECCOv4r4 over 1992–2017.

The interannual SPNA salt content variations in Fig. 6 resemble the LFC variations seen in Fig. 2. The salt content minima in 1994 and 2016 correspond to the SPNA freshening events discussed in section 3. Fig. 6 shows that these freshening events were mainly associated with declining advection in ECCOv4r4. Diffusion counteracts them, but is weaker.

The contribution of advection to the SPNA salt anomalies in Fig. 6 is the sum of horizontal exchange across the two boundaries at 45°N and 65°N , and vertical exchange across 200m. Of these terms, the advective flux across 45°N is relatively large and is strongly anti-correlated with advective flux across 200m (they nearly sum to zero; not shown). That means salt anomalies enter the SPNA control volume from the south, and mainly leave it by sinking across 200m. This exchange resembles the AMOC in the SPNA. In contrast, advective salt flux anomalies across 65°N are relatively smaller, by a factor of about four. The sum of the advective fluxes across 45°N , 65°N , and 200m (red line in Fig. 6) is relatively small compared to these individual advective terms. For the diffusive salt flux anomalies in Fig. 6 (green line), the flux across 200m dominates.

Hence, for upper 200m SPNA ECCOv4r4 salt anomalies, Arctic/SPNA salt exchange is an important (although subdominant) process alongside vertical exchange and horizontal exchange from the south. The role of the Arctic decreasing salt content trend seen in Fig. 5 (upper panel, black line) on the SPNA is unclear, however. Further study of the advective exchange across 65°N is required to elucidate it, such as decomposing the net 65°N flux into southbound Arctic salt import into the SPNA, and northbound export.

6. Summary, open questions, and discussion

On the evidence from the published studies summarized above, and from the new results that provide a holistic context, the state of knowledge on freshwater variations in the Arctic and SPNA is as follows:

- Interannual Arctic freshwater fluctuations clearly exist, which appear to be natural. In addition, a decadal freshening trend exists, which appears to be anthropogenic.
- Arctic Ocean freshwater export to the SPNA is known to fluctuate naturally on interannual periods with several export anomalies thought to have occurred in the last 50–100 years.
- Interannual SPNA freshwater fluctuations (GSAs) clearly exist. They appear to be natural (not forced by anthropogenic effects), with no sign yet of a decadal freshening trend from the north. SPNA fresh anomalies seem to involve longer SPNA residence times, more Arctic water, and less subtropical water. Fluctuations in SPNA air/sea interaction and the AMOC are potentially important too. But the relative roles of these different processes, and their ultimate causes are still obscure.
- Climate model projections suggest that Arctic freshwater accumulation will continue, and Arctic freshwater export fluxes will increase in the 21st century, which will freshen the SPNA. Projections suggest that the anthropogenic freshening signal will emerge in the 2020s (Davis Strait, freshwater flux; Fram Strait ratio of liquid to solid freshwater fluxes).
- Climate model projections suggest that in the 21st century the SPNA AMOC will weaken. There is a low-likelihood, high-impact possibility that the AMOC will weaken irreversibly.

In the light of this knowledge, some leading open questions are:³

- (i) When will Arctic anthropogenic freshening be detected in the SPNA?
- (ii) What is the fingerprint of Arctic anthropogenic freshening in the SPNA and how will it be detected in the SPNA with the current observing network (if at all)?
- (iii) When will Arctic anthropogenic freshening affect SPNA circulation?
- (iv) What is the fingerprint of this circulation change and how will it be detected with the current observing network (if at all)?

To answer these questions on SPNA anthropogenic freshening we require improved understanding of the mechanisms of SPNA salinity variability. Mechanistic understanding is essential to distinguish natural from anthropogenic variations (among several reasons), and to thus characterize the fingerprints of anthropogenic freshening. We hypothesize the following sequence of events: (a) The first Arctic anthropogenic SPNA freshening signals to emerge will be of small amplitude and therefore dynamically passive (not affect the circulation, namely a kinematic mechanism). (b) Dynamically-active Arctic SPNA anthropogenic freshening signals will follow and will weaken the AMOC. As the initial dynamical freshening effects will be of small amplitude, they will affect the AMOC in a linear and, therefore reversible, way. (c) Any subsequent large amplitude Arctic SPNA anthropogenic freshening signals increase the risk of a non-linear irreversible AMOC weakening. The implications of SPNA freshening on the AMOC in steps (b) and (c) also need to be better understood, especially as they pertain to climate impacts.

It is important to recognize that the SPNA may freshen due to anthropogenic effects that are unrelated to Arctic Ocean freshwater export, such as forced Greenland Ice Sheet melt [Luo et al., 2016] or forced changes to the NAO [Kim et al., 2021] or changes associated with anthropogenic aerosols [Booth et al., 2012]. It remains to be established if the AMOC weakening in (b) will be detectable with the present or future observing network (we know of no studies on this

³This list is, of course, incomplete and somewhat subjective. It focuses on the putative impacts of anthropogenic Arctic freshening on the SPNA and AMOC weakening, but other interesting questions abound.

question). It is also possible that the AMOC will weaken for reasons other than an Arctic SPNA anthropogenic freshening signal.

To address the open questions (i)–(iv) the community should:

- Maintain the current observing network, such as the Arctic and SPNA hydrographic measurements and gateway flux observatories.⁴ No alternative method is known to observe the freshening signals.
- Expedite data dissemination, analysis, and synthesis. In some cases, years have passed before data from *in-situ* instruments have been processed and made public. Support is needed to facilitate and accelerate this pipeline.
- Extend and refine dynamically-consistent reanalyses, such as ECCOv4r4. These state estimates are our best (albeit imperfect and provisional) tools to track and understand the basin-scale, decadal stratification and circulation changes.
- Study and refine coupled climate models to resolve Arctic Ocean biases, especially in the Atlantic Water, the halocline, and the surface Polar Water layer, and thereby decrease the model spread in projected salinity changes [Khosravi et al., 2022, Shu et al., 2023].
- Perform consistent, robust budget analyses (like those in Figs. 2, 5, 6). Some past studies have been plagued by ambiguities surrounding reference salinities [Bacon et al., 2015, Schauer and Losch, 2019]. Robust interpretation methods are now known, however, (for example, Tsubouchi et al. 2018); and should be universally adopted. Moreover, the sensitivity of budget analyses to choice of variable (LFC, salt), control volume (full-depth, upper ocean; whole SPNA, eastern SPNA), and data source (state estimates, circulation models) should be explored.
- Observe and understand SPNA freshwater dispersion. In particular, the processes controlling transport of Arctic freshwater off the Greenland and Canadian shelves into the deep SPNA occur at small space-time scales and are poorly observed, modelled, and understood [Stolzenberger et al., 2022, Vellinga et al., 2008].
- Characterize the fingerprint of Arctic anthropogenic freshening in the SPNA and recommend strategies to observe it. An unprecedented opportunity exists to anticipate and observe fresh anomalies move through the system [Haine, 2021].

The aim of these activities is to elucidate the spread of Arctic anthropogenic freshening into the SPNA. They will establish the plausibility of the Arctic freshwater export process as an agent to change the SPNA, the AMOC, and thereby contribute to the wider debate on SPNA anthropogenic change.

Data Accessibility. The ECCO datasets are publicly available on the SciServer system [Medvedev et al., 2016] and at podaac.jpl.nasa.gov/ECCO. The EN4 data are available at www.metoffice.gov.uk/hadobs/en4/.

Authors' Contributions. TWNH conceived of and designed the study, and drafted the manuscript. AJS carried out the data analysis and drafted several of the figures. WJ developed software for the Lagrangian particle analysis. All authors read and approved the manuscript.

Competing Interests. The author(s) declare that they have no competing interests.

Funding. Work on this paper was supported by National Aeronautics and Space Administration grant 80NSSC20K0823 and Johns Hopkins University.

Acknowledgements. TWNH thanks the meeting organizers and the Royal Society for the invitation to present this paper and for travel support. Discussions with An Nguyen and Martha Buckley were valuable, and we appreciate the comments of three anonymous reviewers.

⁴For the gateway flux observations, see Wang et al. [2023], and references therein. For hydrographic observations, ice-tethered profilers [Toole et al., 2011] and the Argo program are particularly valuable. The Overturning in the Subpolar North Atlantic Program (OSNAP) is important for SPNA fluxes and hydrographic changes [Li et al., 2021]. For a comprehensive framework to observe the Arctic Ocean, see Lee et al. [2019]. For a comprehensive list of observations used to constrain ECCOv4r4, see Fukumori et al. [2023, 2021b]; Nguyen et al. [2021] is also useful.

Methods

(a) ECCO Ocean state estimate

The Estimating the Circulation and Climate of the Ocean (ECCO) state estimate is a solution to the Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al. 1997). The solution is computed by fitting the MITgcm fields to several hundred million satellite (altimetry, sea surface temperature, sea surface salinity, gravimetry) and *in-situ* (temperature, salinity) ocean observations for the period of satellite altimetry [Forget et al., 2015, Wunsch and Heimbach, 2007, Wunsch et al., 2009]. To produce the state estimate, the surface forcing, initial conditions, and mixing coefficients are adjusted within their respective uncertainties. As the state estimate is a data-constrained solution to the free-running MITgcm, the solution is dynamically-consistent and it avoids unphysical nudges. Thus, closed, physically-realistic salt budgets can be computed, such as in Figs. 5 and 6. In this paper, we use ECCO version 4 release 4 (ECCOV4r4, Fukumori et al. 2023, 2018, 2021b). The ECCOV4r4 solution is global and spans 1992–2017. The horizontal resolution is 1° and there are 50 vertical levels whose thicknesses range between 10m near the surface and 450m near the bottom.

(b) Ocean reanalysis: EN4

EN4 is a gridded global dataset for ocean temperature and salinity compiled by the United Kingdom Met Office (Good et al. 2013; this paper also explains the origin of the “EN4” name). It spans the period 1900–present with quality control checks and bias removal corrections applied following Gouretski and Reseghetti [2010]. We use EN.4.2.2 for our analysis.

(c) Lagrangian particle analysis

The Lagrangian particle backtracking in Fig. 4 is performed using the seaduck open-source Python software, available at github.com/MaceKuaiv/seaduck. The algorithm uses analytic formulae to compute the Lagrangian trajectories in three dimensions, assuming piecewise-constant-in time velocity fields and linear interpolation in space. The calculations use monthly-averaged ECCOV4r4 velocity fields, but results are essentially unchanged if daily-averaged velocity fields are used instead. Results are also essentially unchanged if the number of particles is increased by a factor of eight.

(d) Salt budget analysis

The salt budgets shown in Figs. 5, 6 are derived as follows. The equation for salinity S reads

$$\frac{\partial S}{\partial t} = -\nabla \cdot (\mathbf{u}S) - \nabla \cdot \mathbf{F}_d + \mathcal{F}_S, \quad (6.1)$$

where \mathbf{F}_d is the diffusive flux and \mathcal{F}_S is the salinity forcing due to salt exchange with sea ice. The other terms assume their conventional meanings. Note that no air/sea exchange of salt occurs. Integrating this equation over a fixed control volume V that is bounded by surface A gives

$$\int_V \frac{\partial S}{\partial t} dV = - \int_A u_\perp S dA - \int_A F_{d,\perp} dA + \int_V \mathcal{F}_S dV,$$

where Gauss’ theorem has been applied to the divergent terms in (6.1) and the \perp subscript indicates the component perpendicular to surface A . Integrating over time yields the mass of salt, $M_S(t)$:

$$M_S(t) \equiv \rho_0 \int_V \frac{\partial S}{\partial t} dV dt' = -\rho_0 \int_A \int_A u_\perp S dA dt' - \rho_0 \int_A \int_A F_{d,\perp} dA dt' + \rho_0 \int_V \int_V \mathcal{F}_S dV dt',$$

where ρ_0 is the reference density of seawater. The four terms in this equation are called “total”, “advection”, “diffusion,” and “sea ice” in Figs. 5 and 6.

References

- K. Aagaard and E. C. Carmack. The role of sea ice and other fresh water in the arctic circulation. *J. Geophys. Res.*, 94(C10):14485, 1989. doi: 10.1029/jc094ic10p14485.
- David I. Armstrong McKay, Arie Staal, Jesse F. Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah E. Cornell, Johan Rockström, and Timothy M. Lenton. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, 377(6611), September 2022. doi: 10.1126/science.abn7950.
- Helene Asbjørnsen, Helen L. Johnson, and Marius Årthun. Variable Nordic Seas inflow linked to shifts in North Atlantic circulation. *J. Climate*, pages 7057–7071, 2021. doi: 10.1175/jcli-d-20-0917.1.
- Sheldon Bacon, Yevgeny Aksenov, Stephen Fawcett, and Gurvan Madec. Arctic mass, freshwater and heat fluxes: methods and modelled seasonal variability. *Phil. Trans. R. Soc. Lond. A*, 373(2052):20140169, October 2015. doi: 10.1098/rsta.2014.0169.
- Igor M. Belkin. Propagation of the “Great Salinity Anomaly” of the 1990s around the northern North Atlantic. *Geophys. Res. Lett.*, 31(8), 2004. doi: 10.1029/2003GL019334.
- Igor M. Belkin, Sydney Levitus, John Antonov, and Svend-Aage Malmberg. “Great Salinity Anomalies” in the North Atlantic. *Prog. Oceanogr.*, 41(1):1–68, January 1998. doi: 10.1016/s0079-6611(98)00015-9.
- Arne Biastoch, Claus W. Böning, Julia Getzlaff, Jean-Marc Molines, and Gurvan Madec. Causes of interannual–decadal variability in the meridional overturning circulation of the midlatitude north atlantic ocean. *Journal of Climate*, 21(24):6599–6615, December 2008. doi: 10.1175/2008jcli2404.1.
- T. C. Biló, F. Straneo, J. Holte, and I. A.-A. Le Bras. Arrival of new Great Salinity Anomaly weakens convection in the Irminger Sea. *Geophys. Res. Lett.*, 49(11), 2022. doi: 10.1029/2022gl098857.
- Ben B. Booth, Nick J. Dunstone, Paul R. Halloran, Timothy Andrews, and Nicolas Bellouin. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, 484(7393):228–232, April 2012. doi: 10.1038/nature10946.
- Harry L. Bryden, William E. Johns, Brian A. King, Gerard McCarthy, Elaine L. McDonagh, Ben I. Moat, and David A. Smeed. Reduction in ocean heat transport at 26°N since 2008 cools the eastern subpolar gyre of the North Atlantic ocean. *J. Climate*, 33(5):1677–1689, March 2020. doi: 10.1175/jcli-d-19-0323.1.
- C. W. Böning, E. Behrens, A. Biastoch, K. Getzlaff, and J. L. Bamber. Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience*, 9(7):523–527, June 2016. doi: 10.1038/ngeo2740.
- L. Caesar, G. D. McCarthy, D. J. R. Thornalley, N. Cahill, and S. Rahmstorf. Current atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience*, 14(3):118–120, February 2021. doi: 10.1038/s41561-021-00699-z.
- W. Cheng, J. C. H. Chiang, and D. Zhang. Atlantic meridional overturning circulation (AMOC) in CMIP5 models: RCP and historical simulations. *J. Climate*, 26(18):7187–7197, September 2013. doi: 10.1175/jcli-d-12-00496.1.
- R. G. Curry and C. Mauritzen. Dilution of the northern North Atlantic Ocean in recent decades. *Science*, 308:1772–1774, 2005. doi: 10.1126/science.1109477.
- Damien Desbruyères, Léon Chafik, and Guillaume Maze. A shift in the ocean circulation has warmed the subpolar North Atlantic Ocean since 2016. *Communications Earth & Environment*, 2(1), February 2021. doi: 10.1038/s43247-021-00120-y.
- Damien G. Desbruyères, Herlé Mercier, Guillaume Maze, and Nathalie Daniault. Surface predictor of overturning circulation and heat content change in the subpolar North Atlantic. *Ocean Science*, 15(3):809–817, June 2019. doi: 10.5194/os-15-809-2019.
- Robert R Dickson, Jens Meincke, Svend-Aage Malmberg, and Arthur J Lee. The “Great Salinity Anomaly” in the northern North Atlantic 1968–1982. *Prog. Oceanogr.*, 20(2):103–151, 1988. doi: 10.1016/0079-6611(88)90049-3.
- H. D. Dooley, J. H. A. Martin, and D. J. Ellett. Abnormal hydrographic conditions in the northeast atlantic during the 1970s. *Rapp PV Reun Cons Int Explor Mer*, 185:179–187, 1984.

- Victoria L. Ford and Oliver W. Frauenfeld. Arctic precipitation recycling and hydrologic budget changes in response to sea ice loss. *Glob. Planet. Change*, 209:103752, February 2022. doi: 10.1016/j.gloplacha.2022.103752.
- G. Forget, J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch. ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geoscientific Model Development*, 8(10):3071–3104, October 2015. doi: 10.5194/gmd-8-3071-2015.
- Alan D. Fox, Arne Biastoch, Stuart A. Cunningham, Neil Fraser, Patricia Handmann, N. Penny Holliday, Clare Johnson, Torge Martin, Marilena Oltmanns, Willi Rath, Siren Rühls, Alejandra Sanchez-Franks, and Christina Schmidt. Exceptional freshening and cooling in the eastern subpolar North Atlantic caused by reduced Labrador Sea surface heat loss. *Ocean Sci.*, April 2022. doi: 10.5194/os-2022-18.
- Yao Fu, Feili Li, Johannes Karstensen, and Chunzai Wang. A stable Atlantic Meridional Overturning Circulation in a changing North Atlantic Ocean since the 1990s. *Science Advances*, 6(48), November 2020. doi: 10.1126/sciadv.abc7836.
- I. Fukumori, O. Wang, I. Fenty, G. Forget, P. Heimbach, and R. M. Ponte. ECCO central estimate (version 4 release 4). Technical report, ECCO Consortium, 2023. URL <https://ecco-group.org/products-ECCO-V4r4.htm>.
- Ichiro Fukumori, Patrick Heimbach, Rui M. Ponte, and Carl Wunsch. A dynamically consistent, multi-variable ocean climatology. *Bull. Amer. Meteor. Soc.*, 99(10):2107–2128, October 2018. doi: 10.1175/BAMS-D-17-0213.1.
- Ichiro Fukumori, Ou Wang, and Ian Fenty. Causal mechanisms of sea-level and freshwater content change in the Beaufort Sea. *J. Phys. Oceanogr.*, August 2021a. doi: 10.1175/jpo-d-21-0069.1.
- Ichiro Fukumori, Ou Wang, Ian Fenty, Gael Forget, Patrick Heimbach, and Rui M. Ponte. Synopsis of the ECCO central production global ocean and sea-ice state estimate, version 4 release 4. Technical report, ECCO Consortium, 2021b.
- Katharine A. Giles, Seymour W. Laxon, Andy L. Ridout, Duncan J. Wingham, and Sheldon Bacon. Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nature Geoscience*, 5(3):194–197, January 2012. doi: 10.1038/NGEO1379.
- Simon A. Good, Matthew J. Martin, and Nick A. Rayner. EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *J. Geophys. Res.*, 118(12):6704–6716, December 2013. doi: 10.1002/2013jc009067.
- Viktor Gouretski and Franco Reseghetti. On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database. *Deep Sea Res., Part I*, 57(6):812–833, 2010. doi: 10.1016/j.dsr.2010.03.011.
- T. W. N. Haine. Arctic Ocean freshening linked to anthropogenic climate change: All hands on deck. *Geophys. Res. Lett.*, November 2020. doi: 10.1029/2020GL090678.
- Thomas W. N. Haine. A conceptual model of polar overturning circulations. *J. Phys. Oceanogr.*, 51(3):727–744, June 2021. doi: 10.1175/JPO-D-20-0139.1.
- Thomas W. N. Haine, Beth Curry, Rüdiger Gerdes, Edmond Hansen, Michael Karcher, Craig Lee, Bert Rudels, Gunnar Spreen, Laura de Steur, Kial D. Stewart, and Rebecca Woodgate. Arctic freshwater export: Status, mechanisms, and prospects. *Glob. Planet. Change*, 125:13–35, February 2015. doi: 10.1016/j.gloplacha.2014.11.013.
- Céline Heuzé, Hannah Zanowski, Salar Karam, and Morven Muilwijk. The deep arctic ocean and fram strait in CMIP6 models. *J. Climate*, 36(8):2551–2584, 2023. doi: 10.1175/jcli-d-22-0194.1.
- N. P. Holliday. Air-sea interaction and circulation changes in the northeast Atlantic. *J. Geophys. Res.*, 108(C8), 2003. doi: 10.1029/2002jc001344.
- N. P. Holliday, S. Bacon, S. A. Cunningham, S. F. Gary, J. Karstensen, B. A. King, F. Li, and E. L. Mcdonagh. Subpolar north atlantic overturning and gyre-scale circulation in the summers of 2014 and 2016. *J. Geophys. Res.*, 123(7):4538–4559, 2018. doi: 10.1029/2018jc013841.
- N. Penny Holliday, Manfred Bersch, Barbara Berx, Léon Chafik, Stuart Cunningham, Cristian Florindo-López, Hjálmar Hátún, William Johns, Simon A. Josey, Karin Margretha H. Larsen, Sandrine Mulet, Marilena Oltmanns, Gilles Reverdin, Tom Rossby, Virginie Thierry, Hedinn Valdimarsson, and Igor Yashayaev. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Comm.*, 11(1), January 2020. doi: 10.1038/s41467-020-14474-y.

- James W. Hurrell, M. M. Holland, P. R. Gent, S. Ghan, Jennifer E. Kay, P. J. Kushner, J.-F. Lamarque, W. G. Large, D. Lawrence, K. Lindsay, W. H. Lipscomb, M. C. Long, N. Mahowald, D. R. Marsh, R. B. Neale, P. Rasch, S. Vavrus, M. Vertenstein, D. Bader, W. D. Collins, J. J. Hack, J. Kiehl, and S. Marshall. The community earth system model: A framework for collaborative research. *Bull. Amer. Meteor. Soc.*, 94(9):1339–1360, 2013. doi: 10.1175/bams-d-12-00121.1.
- Sirpa Häkkinen, Peter B. Rhines, and Denise L. Worthen. Warm and saline events embedded in the meridional circulation of the northern North Atlantic. *J. Geophys. Res.*, 116(C3), March 2011. doi: 10.1029/2010jc006275.
- IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021.
- Laura C. Jackson, Arne Biastoch, Martha W. Buckley, Damien G. Desbruyères, Eleanor Frajka-Williams, Ben Moat, and Jon Robson. The evolution of the North Atlantic Meridional Overturning Circulation since 1980. *Nature Reviews Earth & Environment*, 3(4):241–254, March 2022. doi: 10.1038/s43017-022-00263-2.
- Alexandra Jahn and Rory Laiho. Forced changes in the Arctic freshwater budget emerge in the early 21st century. *Geophys. Res. Lett.*, 47(15), August 2020. doi: 10.1029/2020gl088854.
- H. L. Johnson, S. B. Cornish, Y. Kostov, E. Beer, and C. Lique. Arctic Ocean freshwater content and its decadal memory of sea-level pressure. *Geophys. Res. Lett.*, 45(10):4991–5001, May 2018. doi: 10.1029/2017gl076870.
- Simon A. Josey and Robert Marsh. Surface freshwater flux variability and recent freshening of the North Atlantic in the eastern subpolar gyre. *J. Geophys. Res.*, 110(C5), 2005. doi: 10.1029/2004JC002521.
- T. Karpouzoglou, L. de Steur, L. H. Smedsrud, and H. Sumata. Observed changes in the Arctic freshwater outflow in Fram Strait. *J. Geophys. Res.*, 127(3), February 2022. doi: 10.1029/2021jc018122.
- J. E. Kay, C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J. M. Arblaster, S. C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.-F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein. The community earth system model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, 96(8):1333–1349, August 2015. doi: 10.1175/bams-d-13-00255.1.
- Narges Khosravi, Qiang Wang, Nikolay Koldunov, Claudia Hinrichs, Tido Semmler, Sergey Danilov, and Thomas Jung. The arctic ocean in CMIP6 models: Biases and projected changes in temperature and salinity. *Earth's Future*, 10(2), February 2022. doi: 10.1029/2021ef002282.
- K. Halimeda Kilbourne, Alan D. Wanamaker, Paola Moffa-Sanchez, David J. Reynolds, Daniel E. Amrhein, Paul G. Butler, Geoffrey Gebbie, Marlos Goes, Malte F. Jansen, Christopher M. Little, Madelyn Mette, Eduardo Moreno-Chamarro, Pablo Ortega, Bette L. Otto-Bliesner, Thomas Rossby, James Scourse, and Nina M. Whitney. Atlantic circulation change still uncertain. *Nature Geoscience*, 15(3):165–167, February 2022. doi: 10.1038/s41561-022-00896-4.
- Who M. Kim, Stephen Yeager, and Gokhan Danabasoglu. Revisiting the causal connection between the Great Salinity Anomaly of the 1970s and the shutdown of Labrador Sea deep convection. *J. Climate*, 34(2):675–696, October 2021. doi: 10.1175/JCLI-D-20-0327.1.
- Yavor Kostov, Helen L. Johnson, David P. Marshall, Patrick Heimbach, Gael Forget, N. Penny Holliday, M. Susan Lozier, Feili Li, Helen R. Pillar, and Timothy Smith. Distinct sources of interannual subtropical and subpolar atlantic overturning variability. *Nature Geoscience*, 14(7): 491–495, May 2021. doi: 10.1038/s41561-021-00759-4.
- Vimal Koul, Jan-Erik Tesdal, Manfred Bersch, Hjálmar Hátún, Sebastian Brune, Leonard Borchert, Helmuth Haak, Corinna Schrum, and Johanna Baehr. Unraveling the choice of the north Atlantic subpolar gyre index. *Scientific Reports*, 10(1), January 2020. doi: 10.1038/s41598-020-57790-5.
- Mojib Latif, Jing Sun, Martin Visbeck, and M. Hadi Bordbar. Natural variability has dominated atlantic meridional overturning circulation since 1900. *Nature Climate Change*, 12(5):455–460, April 2022. doi: 10.1038/s41558-022-01342-4.

- Craig M. Lee, Sandy Starkweather, Hajo Eicken, Mary-Louise Timmermans, Jeremy Wilkinson, Stein Sandven, Dmitry Dukhovskoy, Sebastian Gerland, Jacqueline Grebmeier, Janet M. Intrieri, Sung-Ho Kang, Molly McCammon, An T. Nguyen, Igor Polyakov, Benjamin Rabe, Hanne Sagen, Sophie Seeyave, Denis Volkov, Agnieszka Beszczynska-Möller, Léon Chafik, Matthew Dzieciuch, Gustavo Goni, Torill Hamre, Andrew Luke King, Are Olsen, Roshin P. Raj, Thomas Rossby, Øystein Skagseth, Henrik Søiland, and Kai Sørensen. A framework for the development, design and implementation of a sustained arctic ocean observing system. *Frontiers in Marine Science*, 6, August 2019. doi: 10.3389/fmars.2019.00451.
- Timothy M. Lenton, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen, and Hans Joachim Schellnhuber. Climate tipping points — too risky to bet against. *Nature*, 575(7784):592–595, November 2019. doi: 10.1038/d41586-019-03595-0.
- Feili Li, M. Susan Lozier, N. Penny Holliday, William E. Johns, Isabela A. Le Bras, Ben I. Moat, Stuart A. Cunningham, and M. Femke de Jong. Observation-based estimates of heat and freshwater exchanges from the subtropical north atlantic to the arctic. *Prog. Oceanogr.*, 197: 102640, 2021. doi: 10.1016/j.pocean.2021.102640.
- Johannes Lohmann and Peter D. Ditlevsen. Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proceedings of the National Academy of Sciences*, 118(9), February 2021. doi: 10.1073/pnas.2017989118.
- Hao Luo, Renato M. Castelao, Asa K. Rennermalm, Marco Tedesco, Annalisa Bracco, Patricia L. Yager, and Thomas L. Mote. Oceanic transport of surface meltwater from the southern Greenland ice sheet. *Nature Geoscience*, 9(7):528–532, April 2016. doi: 10.1038/ngeo2708.
- G. E. Manucharyan and P. E. Isachsen. Critical role of continental slopes in halocline and eddy dynamics of the ekman-driven Beaufort Gyre. *J. Geophys. Res.*, 124(4):2679–2696, April 2019. doi: 10.1029/2018jc014624.
- G. E. Manucharyan, M. A. Spall, and A. F. Thompson. A theory of the wind-driven Beaufort Gyre variability. *J. Phys. Oceanogr.*, 46(11):3263–3278, October 2016. ISSN 0094-8276. doi: 10.1175/JPO-D-16-0091.1.
- Georgy E. Manucharyan and Michael A. Spall. Wind-driven freshwater buildup and release in the Beaufort Gyre constrained by mesoscale eddies. *Geophys. Res. Lett.*, 43(1):273–282, January 2016. doi: 10.1002/2015gl065957.
- John Marshall, Alistair Adcroft, Chris Hill, Lev Perelman, and Curt Heisey. A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. *J. Geophys. Res.*, 102(C3):5753–5766, March 1997. doi: 10.1029/96jc02775.
- Juliana M. Marson, Laura C. Gillard, and Paul G. Myers. Distinct ocean responses to Greenland’s liquid runoff and iceberg melt. *J. Geophys. Res.*, 126(12), November 2021. doi: 10.1029/2021jc017542.
- T. Martin, M. Steele, and J. Zhang. Seasonality and long-term trend of Arctic Ocean surface stress in a model. *J. Geophys. Res.*, 119:1723–1738, 2014. doi: 10.1002/2013JC009425.
- Michelle R. McCrystal, Julianne Stroeve, Mark Serreze, Bruce C. Forbes, and James A. Screen. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nature Communications*, 12(1), November 2021. doi: 10.1038/s41467-021-27031-y.
- D. Medvedev, G. Lemson, and M. Rippin. SciServer compute. In *Proceedings of the 28th International Conference on Scientific and Statistical Database Management - SSDBM '16*. ACM Press, 2016. doi: 10.1145/2949689.2949700.
- Gianluca Meneghello, John Marshall, Jean-Michel Campin, Edward Doddridge, and Mary-Louise Timmermans. The ice-ocean governor: Ice-ocean stress feedback limits Beaufort Gyre spin-up. *Geophys. Res. Lett.*, 45(20):11,293–11,299, October 2018. doi: 10.1029/2018gl080171.
- P. Moffa-Sánchez, E. Moreno-Chamarro, D. J. Reynolds, P. Ortega, L. Cunningham, D. Swingedouw, D. E. Amrhein, J. Halfar, L. Jonkers, J. H. Jungclaus, K. Perner, A. Wanamaker, and S. Yeager. Variability in the northern north atlantic and arctic oceans across the last two millennia: A review. *Paleoceanography and Paleoclimatology*, 34(8):1399–1436, 2019. doi: 10.1029/2018pa003508.
- Morven Muilwijk, Aleks Nummelin, Céline Heuzé, Igor V. Polyakov, Hannah Zanowski, and Lars H. Smedsrud. Divergence in climate model projections of future arctic atlantification. *J. Climate*, 36(6):1727–1748, 2023. doi: 10.1175/jcli-d-22-0349.1.

- An T. Nguyen, Helen Pillar, Victor Ocaña, Arash Bigdeli, Timothy A. Smith, and Patrick Heimbach. The arctic subpolar gyre state estimate: Description and assessment of a data-constrained, dynamically consistent ocean-sea ice estimate for 2002–2017. *J. Advances Model. Earth Sys.*, 13(5), 2021. doi: 10.1029/2020ms002398.
- Dirk Notz and Jochem Marotzke. Observations reveal external driver for Arctic sea-ice retreat. *Geophys. Res. Lett.*, 39(8), April 2012. doi: 10.1029/2012GL051094.
- Christopher G. Piecuch, Rui M. Ponte, Christopher M. Little, Martha W. Buckley, and Ichiro Fukumori. Mechanisms underlying recent decadal changes in subpolar North Atlantic Ocean heat content. *J. Geophys. Res.*, 122(9):7181–7197, September 2017. doi: 10.1002/2017jc012845.
- A. Proshutinsky, R. Krishfield, J. M. Toole, M.-L. Timmermans, W. Williams, S. Zimmermann, M. Yamamoto-Kawai, T. W. K. Armitage, D. Dukhovskoy, E. Golubeva, G. E. Manucharyan, G. Platov, E. Watanabe, T. Kikuchi, S. Nishino, M. Itoh, S.-H. Kang, K.-H. Cho, K. Tateyama, and J. Zhao. Analysis of the Beaufort Gyre freshwater content in 2003–2018. *J. Geophys. Res.*, 124(12):9658–9689, December 2019. doi: 10.1029/2019jc015281.
- A. Y. Proshutinsky and M. A. Johnson. Two circulation regimes of the wind-driven Arctic Ocean. *J. Geophys. Res.*, 102(C6):12493–12514, June 1997. doi: 10.1029/97jc00738.
- A. Y. Proshutinsky, R. H. Bourke, and F. A. McLaughlin. The role of the Beaufort Gyre in Arctic climate variability: Seasonal to decadal climate scales. *Geophys. Res. Lett.*, 23, 2002. doi: 10.1029/2002GL015847.
- B. Rabe, M. Karcher, F. Kauker, U. Schauer, J. M. Toole, R. A. Krishfield, S. Pisarev, T. Kikuchi, and J. Su. Arctic Ocean basin liquid freshwater storage trend 1992–2012. *Geophys. Res. Lett.*, 41(3): 961–968, February 2014. doi: 10.1002/2013gl058121.
- Jon Robson, Pablo Ortega, and Rowan Sutton. A reversal of climatic trends in the North Atlantic since 2005. *Nature Geoscience*, 9(7):513–517, June 2016. doi: 10.1038/ngeo2727.
- Benjamin M. Sanderson, Yangyang Xu, Claudia Tebaldi, Michael Wehner, Brian O'Neill, Alexandra Jahn, Angeline G. Pendergrass, Flavio Lehner, Warren G. Strand, Lei Lin, Reto Knutti, and Jean Francois Lamarque. Community climate simulations to assess avoided impacts in 1.5 and 2°C futures. *Earth System Dynamics*, 8(3):827–847, September 2017. doi: 10.5194/esd-8-827-2017.
- Ursula Schauer and Martin Losch. “Freshwater” in the ocean is not a useful parameter in climate research. *J. Phys. Oceanogr.*, 49(9):2309–2321, 2019. doi: 10.1175/jpo-d-19-0102.1.
- K. Schulz, A. T. Nguyen, and H. R. Pillar. An improved and observationally-constrained melt rate parameterization for vertical ice fronts of marine terminating glaciers. *Geophys. Res. Lett.*, 49(18), 2022. doi: 10.1029/2022gl100654.
- Qi Shu, Qiang Wang, Chuncheng Guo, Zhenya Song, Shizhu Wang, Yan He, and Fangli Qiao. Arctic ocean simulations in the CMIP6 ocean model intercomparison project (OMIP). *Geosci. Mod. Dev.*, 16(9):2539–2563, 2023. doi: 10.5194/gmd-16-2539-2023.
- Amy Solomon, Céline Heuzé, Benjamin Rabe, Sheldon Bacon, Laurent Bertino, Patrick Heimbach, Jun Inoue, Doroteaciro Iovino, Ruth Mottram, Xiangdong Zhang, Yevgeny Aksenov, Ronan McAdam, An Nguyen, Roshin P. Raj, and Han Tang. Freshwater in the Arctic Ocean 2010–2019. *Ocean Science*, 17(4):1081–1102, August 2021. doi: 10.5194/os-17-1081-2021.
- Meric Srokosz, Gokhan Danabasoglu, and Michael Patterson. Atlantic meridional overturning circulation: Reviews of observational and modeling advances—an introduction. *J. Geophys. Res.*, 126(1), 2021. doi: 10.1029/2020jc016745.
- Tricia A. Stadnyk, A. Tefs, M. Broesky, S. J. Déry, P. G. Myers, N. A. Ridenour, K. Koenig, L. Vonderbank, and D. Gustafsson. Changing freshwater contributions to the arctic. *Elementa: Science of the Anthropocene*, 9(1), 2021. doi: 10.1525/elementa.2020.00098.
- K. D. Stewart and T. W. N. Haine. Wind-driven Arctic freshwater anomalies. *Geophys. Res. Lett.*, 40(23):6196–6201, 2013. doi: 10.1002/2013GL058247.
- Sophie Stolzenberger, Roelof Rietbroek, Claudia Wekerle, Bernd Uebbing, and Jürgen Kusche. Simulated signatures of Greenland melting in the North Atlantic: A model comparison with Argo floats, satellite observations, and ocean reanalysis. *J. Geophys. Res.*, 127(11), 2022. doi: 10.1029/2022jc018528.

- H. Stommel. Thermohaline convection with two stable regimes. *Tellus*, 13:224–230, 1961.
- Svein Sundby and Kenneth Drinkwater. On the mechanisms behind salinity anomaly signals of the northern North Atlantic. *Prog. Oceanogr.*, 73(2):190–202, May 2007. doi: 10.1016/j.pocean.2007.02.002.
- Jan-Erik Tesdal and Thomas W. N. Haine. Dominant terms in the freshwater and heat budgets of the subpolar North Atlantic Ocean and Nordic Seas from 1992 to 2015. *J. Geophys. Res.*, 125(10), October 2020. doi: 10.1029/2020JC016435.
- Virginie Thierry, Eric De Boisseson, and Herle Mercier. Interannual variability of the subpolar mode water properties over the Reykjanes Ridge during 1990–2006. *J. Geophys. Res.*, 113(C4), April 2008. doi: 10.1029/2007jc004443.
- John Toole, Richard Krishfield, Mary-Louise Timmermans, and Andrey Proshutinsky. The ice-tethered profiler: Argo of the arctic. *Oceanography*, 24(3):126–135, 2011. doi: 10.5670/oceanog.2011.64.
- Takamasa Tsubouchi, Sheldon Bacon, Yevgeny Aksenov, Alberto C. Naveira Garabato, Agnieszka Beszczynska-Möller, Edmond Hansen, Laura de Steur, Beth Curry, and Craig M. Lee. The Arctic Ocean seasonal cycles of heat and freshwater fluxes: observation-based inverse estimates. *J. Phys. Oceanogr.*, 48(9):2029–2055, September 2018. doi: 10.1175/jpo-d-17-0239.1.
- Michael Vellinga, Bob Dickson, and Ruth Curry. The changing view on how freshwater impacts the Atlantic Meridional Overturning Circulation. In R. R. Dickson, J. Meincke, and P. Rhines, editors, *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, pages 289–313. Springer-Verlag, 2008. doi: 10.1007/978-1-4020-6774-7_13.
- Timo Vihma, James Screen, Michael Tjernström, Brandi Newton, Xiangdong Zhang, Valeria Popova, Clara Deser, Marika Holland, and Terry Prowse. The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. *J. Geophys. Res.*, 121(3):586–620, March 2016. doi: 10.1002/2015jg003132.
- Qiang Wang, Qi Shu, Shizhu Wang, Agnieszka Beszczynska-Moeller, Sergey Danilov, Laura de Steur, Thomas W. N. Haine, Michael Karcher, Craig M. Lee, Paul G. Myers, Igor V. Polyakov, Christine Provost, Øystein Skagseth, Gunnar Spreen, and Rebecca Woodgate. A review of Arctic-Subarctic ocean linkages: past changes, mechanisms and future projections. *Ocean-Land-Atmosphere Research*, 2, 2023. doi: 10.34133/olar.0013.
- W. Weijer, W. Cheng, S. S. Drijfhout, A. V. Fedorov, A. Hu, L. C. Jackson, W. Liu, E. L. McDonagh, J. V. Mecking, and J. Zhang. Stability of the Atlantic Meridional Overturning Circulation: A review and synthesis. *J. Geophys. Res.*, 124(8):5336–5375, August 2019. doi: 10.1029/2019jc015083.
- W. Weijer, W. Cheng, O. A. Garuba, A. Hu, and B. T. Nadiga. CMIP6 models predict significant 21st century decline of the Atlantic Meridional Overturning Circulation. *Geophys. Res. Lett.*, 47(12), June 2020. doi: 10.1029/2019gl086075.
- Wilbert Weijer, Thomas W. N. Haine, Ali H. Siddiqui, Wei Cheng, Milena Veneziani, and Prajvala Kurtakoti. Interactions between the Arctic Mediterranean and the Atlantic Meridional Overturning Circulation: A review. *Oceanography*, 2022. doi: 10.5670/oceanog.2022.130.
- C. Wunsch and P. Heimbach. Practical global oceanic state estimation. *Physica D*, 230:197–208, 2007. doi: 10.1016/j.physd.2006.09.040.
- Carl Wunsch, Patrick Heimbach, Rui Ponte, and Ichiro Fukumori. The global general circulation of the ocean estimated by the ECCO-consortium. *Oceanography*, 22(2):88–103, June 2009. doi: 10.5670/oceanog.2009.41.
- Stephen Yeager and Gokhan Danabasoglu. The origins of late-twentieth-century variations in the large-scale north atlantic circulation. *J. Climate*, 27(9):3222–3247, April 2014. doi: 10.1175/jcli-d-13-00125.1.
- Stephen Yeager, Alicia Karspeck, Gokhan Danabasoglu, Joe Tribbia, and Haiyan Teng. A decadal prediction case study: Late twentieth-century North Atlantic Ocean heat content. *J. Climate*, 25(15):5173–5189, August 2012. doi: 10.1175/jcli-d-11-00595.1.
- Hannah Zanowski, Alexandra Jahn, and Marika M. Holland. Arctic ocean freshwater in CMIP6 ensembles: Declining sea ice, increasing ocean storage and export. *J. Geophys. Res.*, 126(4), March 2021. doi: 10.1029/2020jc016930.

- Jiaxu Zhang, Wilbert Weijer, Michael Steele, Wei Cheng, Tarun Verma, and Milena Veneziani. Labrador Sea freshening linked to Beaufort Gyre freshwater release. *Nature Communications*, 12(1), February 2021. doi: 10.1038/s41467-021-21470-3.
- R. Zhang and G. K. Vallis. Impact of Great Salinity Anomalies on the low-frequency variability of the North Atlantic climate. *J. Climate*, 19(3):470–482, February 2006. doi: 10.1175/jcli3623.1.
- Rong Zhang, Rowan Sutton, Gokhan Danabasoglu, Young-Oh Kwon, Robert Marsh, Stephen G. Yeager, Daniel E. Amrhein, and Christopher M. Little. A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and associated climate impacts. *Rev. Geophys.*, 57(2):316–375, June 2019. doi: 10.1029/2019rg000644.