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Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean

Claus W. Böning[1,*], Erik Behrens[1,2], Arne Biastoch[1] , Klaus Getzlaff[1] & Jonathan Bamber[3]

[1] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany*

[2] *National Institute of Water and Atmospheric Research, Wellington, New Zealand*

[3] *School of Geographical Sciences, University of Bristol, UK*

[*] *Corresponding author*

The Greenland Ice sheet has experienced increasing mass loss since the 1990s[1,2]. The enhanced freshwater flux due to both surface melt and outlet glacier discharge is assuming an increasingly important role in the changing freshwater budget of the subarctic Atlantic[3]. The sustained and increasing freshwater fluxes from Greenland to the surface ocean could lead to a suppression of deep winter convection in the Labrador Sea, with potential ramifications for the strength of the Atlantic meridional overturning circulation (AMOC)[4-6]. Here we assess the impact of the increases in the freshwater fluxes, reconstructed with full spatial resolution[3], using a global ocean circulation model with a grid spacing fine enough to capture the small-scale, eddying transport processes in the subpolar North Atlantic. Our simulations suggest that the invasion of meltwater from the West Greenland shelf has initiated a gradual freshening trend at the surface of the Labrador Sea. While the freshening is still smaller than the variability associated with the episodic 'great salinity anomalies', the accumulation of meltwater may become large enough to progressively dampen the deep winter convection in the coming years. We conclude that the freshwater anomaly has not yet had a significant impact on the Atlantic meridional overturning circulation.

The subpolar North Atlantic (Fig. 1a) plays an important role in the global climate system due to its generation, by deep convection during winter, of North Atlantic Deep Water that feeds the deep limb of the Atlantic meridional overturning circulation (AMOC). While annual formation rates vary strongly, primarily due to the variability in atmospheric conditions[7-9], a progressive anthropogenic freshening of the surface waters bears the potential of a persistent weakening of convection intensities. Satellite observations in conjunction with surface mass balance models provided detailed reconstructions of the non-uniform distribution of Greenland ice-mass trends[2] and the corresponding freshwater discharge into the ocean[3]. The meltwater fluxes show large increasing trends since the mid-1990s, particularly for the south-eastern and western portions of the ice sheet, implying major additional sources of freshwater for the subpolar North Atlantic[10]. Importantly, the ice mass loss has been increasing over time including the most recent years[11].

The fate of this additional discharge is not well understood since a meltwater-related freshening trend is difficult to distinguish from the strong decadal variability in the subarctic freshwater content[12,13]. According to ref. 3, the cumulative freshwater anomaly from the ice sheet as a whole amounted to 3200 km^3 by 2010. From ocean observations it is not possible to infer how much of this input has been retained in the subpolar North Atlantic, and in particular, how much of it has been invading the surface waters of the Labrador Sea where it could impact the winter convection. The spreading of waters off the Greenland shelf is intimately linked to mesoscale (~10-30 km) ocean transport processes; specifically, the invasion of the interior Labrador Sea by low-salinity waters from the West Greenland Current (WGC) system is governed by mesoscale eddies arising from an instability of the WGC at the steep bathymetry off Cape Desolation[14,15]. The eddy-induced flux is important for the stability of the near-surface waters[16] and effectively confines the deep convection to the southwestern Labrador Sea[17]. Ocean model studies[18,19] with enhanced resolutions of 0.1° confirmed the key role of eddy processes in the oceanic response to freshwater flux perturbations; however, the use of idealized flux scenarios in these studies, with perturbations of 0.1-0.5 Sverdrups (Sv; 1 Sv = 10^6 m^3s^{-1}) which exceed the present flux anomalies by an order of magnitude, prevents conclusions about the impact of the actual acceleration in the Greenland melting.

We have assessed the fate and impact of the spatially non-uniform increase in the freshwater flux from Greenland, based on a set of global ocean-sea ice models with increasing resolution devised to capture the critical eddy processes in the subpolar North Atlantic. In the high-resolution case (Fig. 1a), the global model mesh of 0.25° was refined to 0.05° in the North Atlantic between 32°N and 82°N (corresponding to a mesh size of ~3 km in the Labrador Sea; Supplementary S1), providing an improved realism in the simulation of the complex boundary current system[20]. In particular, the model succeeds in generating a wedge of enhanced mesoscale eddy activity in the north-eastern Labrador Sea originating off Cape Desolation (Fig. 1b).

The impact of the increasing Greenland melting trend was determined by comparing a control simulation forced with climatological coastal runoffs (CNTR) to a case (MELT) with a spatially non-uniform, linearly increasing runoff-trend of 16.9 km^3 yr^{-2} following ref. 3, over a 30-year period beginning in 1990 (Fig. 1c). The atmospheric forcing builds on a bulk formulation of air-sea fluxes with prescribed atmospheric data for 1948-2007 developed for global ocean hindcast simulations[21,22]. While the unknown future forcing precludes a prediction of the inter-annually varying state of the ocean, we seek to assess the future evolution of the individual impact of the meltwater, as given by the difference between MELT and CNTR, by continuing both experiments for another 12 years with a repeated atmospheric forcing of the year 2007. The freshwater flux anomalies in MELT were extended by extrapolating the current trend[3]. Until the end of this decade the cumulative runoff anomaly amounts to 7500 km^3. However, less than half of the additional meltwater, about 3000 km^3, is accumulating in the subpolar North Atlantic (Fig. 1c) which represents a relatively small addition to the large decadal changes in the total (0-2000m) freshwater content recorded by refs. 12 and 13 (Fig. 1d). We note that the observed decadal variability is captured by the hindcast simulation (CNTR), with a similar freshening trend during the 1970s and 1980s, and its reversal thereafter.

The progression of the meltwater is illustrated by ‘dyeing’ the additional runoff, i.e., by computing the fate of a dye released with the same source distribution as the freshwater off Greenland (Fig. 2; Supplementary S2). In concurrence with previous studies[18,19,24], highest concentrations are evolving in Baffin Bay, where the runoff from Northwest Greenland is superimposed by the northward flow of meltwater by the WGC, and reinforced by a reduction in the southward volume transport through Davis Strait (cf. ref. 24, 25). Farther south the spreading in the high-resolution model (Fig. 2a) differs from lower resolution simulations in two main respects, as emphasized by the companion experiment using the 0.25°-grid without refinement in the North Atlantic (Fig. 2b): one, in the emergence of a near-surface route inshore of the Gulf Stream, providing an outlet for some fraction of the meltwater into the Mid-Atlantic Bight; two, in the enhanced concentrations over the northern Labrador Sea, owing to the flux by the WGC eddies (cf. ref. 10).

A first inference of the potential relevance of the meltwater signal for the convection intensity can be obtained by contrasting the freshwater anomaly currently developing in the surface layer with the historic episodes of surface freshening[26] around 1970 (known as the "Great Salinity Anomaly", GSA70[27]), the mid-1980s and early 1990s[28] that were associated with pulses of enhanced sea ice export from the Arctic Ocean along the shelf of East Greenland[29]. Estimates of the freshwater discharges vary; however, pertinent to the consideration here, the salinity record for the surface layer (0-300 m) of the Labrador Sea suggests[27] that each of these events amounted to a freshwater anomaly of about 1700 km^3 passing the continental slope region off southwestern Greenland, consistent with an ice export anomaly through Fram Strait of ~2300 km^3 in the years preceding the GSA70[29]. Our model simulation suggests that the accumulation of meltwater in the Labrador Sea is by now reaching half that magnitude (Fig. 1c).

Meltwater-induced trends in the hydrography of the Labrador Sea occur in a rather gradual way (Fig. 3). Throughout the simulation period, the decrease in the surface salinity remains small compared to the inter-annual variability induced (until 2007) by the atmospheric forcing (Supplementary S3). However, the signal is continuously increasing, towards the end of this decade reaching 0.3 in the WGC and 0.1 along the low-salinity wedge extending into the interior Labrador Sea (Figs. 3a,b). To assess the significance of this emerging meltwater signal, it is instructive to contrast the current trend with the surface salinity anomalies occurring during the great salinity anomalies. A manifestation of these events can be seen on the West Greenland shelf where the salinity in CNTR dropped by about 1 (Supplementary S3). The effects in the interior Labrador Sea were smaller, as shown by the record of the GSA70 by former Ocean Weather Ship Bravo (OWS-B)[8] ; its manifestation is also present in the model hindcast .

Obviously, the emerging salinity tendencies in MELT are still small compared to these strong, intermittent freshening pulses.

While not yet of an amplitude comparable to these episodic events, the sustained accumulation of meltwater may have begun to increase the near-surface stability enough to leave a first trace in the intensity of the wintertime convection. Note that the great salinity anomalies, in spite of their similar magnitudes, had considerably different impacts on the convection intensity[30]: while the GSA70, in conjunction with a series of mild winters, effectively shut down deep convection for three consecutive years[8,9], there was no obvious impact of the last anomaly during the phase of harsh winters with very strong convection in the early 1990s. While we thus cannot predict the absolute year-to-year evolution of convection in the future (nor hindcast inter-annual variations beyond 2007), the difference between MELT and CNTR does provide a useful means of isolating the meltwater effect (Fig. 3c; Supplementary S4). Apart from a strong year-to-year variability, primarily reflecting the surface heat loss during winter governed by the imposed atmospheric state, the main signal is the inter-decadal increase from the weak-convection period during the late 1960s and 1970s to a period with maximum intensity during the late 1980s and early 1990s, and its subsequent slackening, in general accordance with previous accounts[30]. Compared to this strong background variability, the effect of the additional meltwater has remained negligible until now; however, it progressively increases during the next years to nearly 30% of the range of variability experienced during the previous decades. We note that the meltwater mainly affects the formation of the dense class of LSW in the Labrador Sea, not the lighter, “upper” LSW formed also in the Irminger Sea (Supplementary S4). A corresponding decline is seen in the depth of winter convection which towards the end of the decade will be curbed by 200-500m (Fig. 3d). The strongest signals occur along the main meltwater pathways: along the offshore edge of the western boundary current off the Labrador continental slope, and in the interior northern Labrador Sea along the path of the WGC eddies.

With an impact on the intensity of convection not emerging before the end of the decade, we cannot yet expect a significant dynamical repercussion of the increased runoff. Accordingly, there is only a first hint of a weak, but meridionally-coherent signal in the AMOC transport emerging towards the end of the simulation period in the MELT-CNTR difference (Supplementary S4). This contrasts with the effect of an idealized freshwater perturbation of larger magnitude. As demonstrated in a sensitivity experiment (I-MELT), an instant increase to a constant flux of 3000 km^3 yr^{-1} (about 0.1 Sv) leads to a rapid dilution of the surface waters (Supplementary S5), a cessation of deep convection after 6-8 years, followed by a rapid slowdown of the AMOC by more than 5 Sv. At that point the accumulated runoff exceeds ~20,000 km^3: under a continuation of the actual trend such a magnitude would be reached around 2040. This has some bearing on the hypothesis[6], that the increase in the ice-mass loss from Greenland could already have begun to restrain the AMOC during the second half of the 20th-century: based on the present simulations we argue that the accumulation of meltwater has not been large enough yet to affect the freshwater budget of the subpolar North Atlantic, precluding a significant impact on the AMOC. Another corollary of our simulations is, however, that the ongoing, and perhaps, accelerating melting-induced freshening of the surface waters in the subpolar North Atlantic may begin to progressively affect the deep water formation, and in turn the AMOC, before clear signals of trends in critical hydrographic properties would become identifiable given the strong interannual variability in many of these fields.

Methods

Methods, including references, and statements of data and code availability are provided in the online version of this paper.

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Author Contributions

All authors conceived the experiments. E. B. implemented the model and performed the experiments. E. B., C. B., K.G. and A. B. analysed the results. C. B. wrote the paper with contributions by all co-authors.

Competing financial interests

The authors declare no competing financial interest.

Figure captions

Figure 1 | Circulation and freshwater content of the subpolar North Atlantic. (a) Snapshot of surface speed in the high-resolution model illustrating the vigorous eddying currents in the northwestern Atlantic as simulated. (b) Mean depth of the March mixed layer (colours; m) and eddy kinetic energy (EKE); c.i. 25 cm^2s^{-2} (100 cm^2s^{-2}) for EKE below (above) 100 cm^2s^{-2}. (c) Cumulated runoff perturbation imposed in MELT using the rate of increase determined by ref. 3 until 2010 (light blue), and its extrapolation through 2019 (dashed light blue), and the simulated freshwater content anomaly in the subpolar North Atlantic (blue), and in the Labrador Sea only (green). (d) Variability of freshwater content in the upper 2000 m of the North Atlantic between 50 - 80°N, derived from the ORAS4 ocean reanalysis data discussed in ref. 23 (grey), and model simulations CNTR (black) and MELT (blue).

Figure 2 | Fate of the additional Greenland runoff. Distribution of vertically-integrated passive tracer content in the last year of MELT (a) in the 0.05°-simulation (VIKING20); (b) same in the 0.25°-simulation (ORCA025).

Figure 3 | Trends in Labrador Sea surface salinity and convection intensity. (a) Sea surface salinity anomaly in the last year of MELT, black box indicating the site of OWS-B (see supplementary information). (b) Meltwater-induced trends in sea surface salinity in the WGC (red box in a) and basin interior (green box) as given by the difference MELT-CNTR. (c) Annual formation rate of Labrador Sea Water (LSW), as given by the increase in the volume of the LSW density layer in the Labrador Sea during the winter convection seasons, for CNTR (black) and MELT (blue). (d) Deviation of March mixed layer depths in MELT from CNTR (average over years 2017-19), in m.