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compiled by Dr. Alvarinho J. Luis

The fate of melting glacial ice in Greenland

Over the past several decades, scientists have observed a significant increase in the melting of glacial land ice on the island of Greenland, spurring concerns about global sea level rise and the long-term effects of atmospheric warming. However, what has been less clear is what happens to this melt water once it enters the ocean.

Now, a team of researchers at the Univ of Georgia has discovered the fate of much of the freshwater that pours into the surrounding oceans as the Greenland ice sheet melts every summer. They published their findings in the journal *Nature Geoscience*.

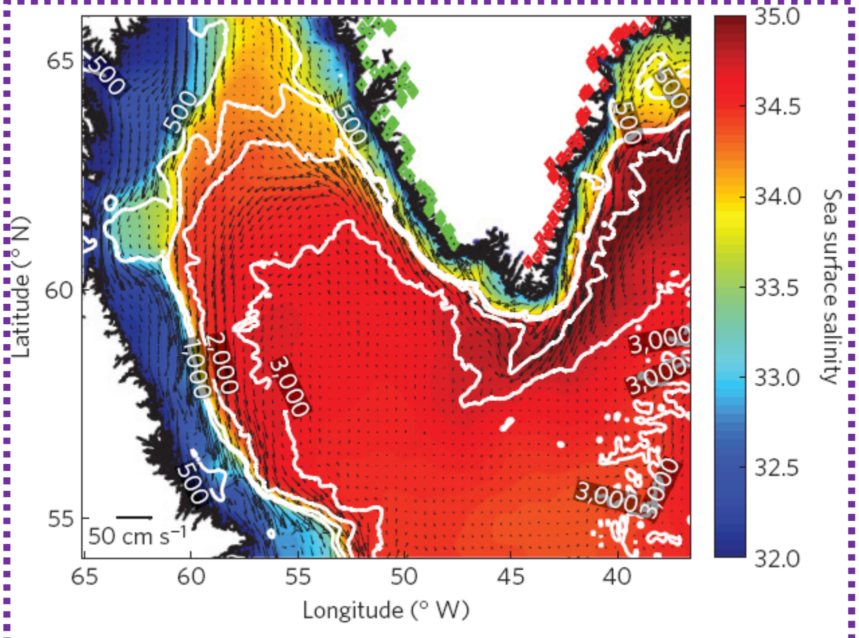
Understanding the fate of meltwater is important, because research has shown that it can carry a variety of nutrients, which may impact biological production in the ocean, said study co-author R. Castelao. There is also evidence that large freshwater inputs could alter ocean currents and affect the normal formation of sea ice.

The researchers created a simulation that tracks melt water runoff under a variety of atmospheric conditions, and they were surprised to discover that most of the melt water found off the west coast of Greenland actually originated from ice on the east coast.

Melt water from Greenland is directed by the surrounding ocean currents, but its fate depends on when and where the runoff occurs and the wind fields driving ocean currents, said study co-author Thomas Mote.

According to the model, wind and ocean currents often transport melt water around the southern tip of Greenland on a westward journey that can take upward of 60 days. After rounding the tip, the melt water is largely deposited into the Labrador Sea, an arm of the Atlantic between Canada's Labrador Peninsula and the east coast of Greenland.

Melt water originating from the west coast of Greenland, on the other hand, is often kept pinned to the coastline by strong winds, which push it northward toward Baffin Bay.



Sea surface salinity (colour map) and surface currents (vectors) averaged from 2008 to 2012. The 500, 1000, 2000 and 3000 m isobaths are shown in white. Green and red symbols show the locations ofWest and East Greenland meltwater runoff inputs, respectively.

This isn't always how melt water from the Greenland ice sheet disperses, as shifts in the prevailing winds can produce very different effects. But scientists must be aware of these shifts in order to fully understand how melt water will affect the environment, Castelao said.

The melt water that comes from the east coast could have different qualities from the melt water on the west coast, including different nutrient compositions. We need to take the origins of this melt water into account when we study the effects of ice sheet melt, as it could impact the oceans differently depending on where it comes from, Castelao said

And this is a problem that is only going to get worse, citing scientific models that suggest the amount of melt water runoff from Greenland could more than double before the end of this century.

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LETTERS

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Oceanic transport of surface meltwater from the southern Greenland ice sheet

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The Greenland ice sheet has undergone accelerating mass losses during recent decades. Freshwater runoff from ice melt can influence fjord circulation and dynamics[1] and the delivery of bioavailable micronutrients to the ocean[2]. It can also have climate implications, because stratification in the adjacent Labrador Sea may influence deep convection and the strength of the Atlantic meridional overturning circulation[3]. Yet, the fate of the meltwater in the ocean remains unclear. Here, we use a high-resolution ocean model to show that only 1–15% of the surface meltwater runoff originating from southwest Greenland is transported westwards. In contrast, up to 50–60% of the meltwater runoff originating from southeast Greenland is transported westwards into the northern Labrador Sea, leading to significant salinity and stratification anomalies far from the coast. Doubling meltwater runoff, as predicted in future climate scenarios, results in a more-than-double increase in anomalies offshore that persists further into the winter. Interannual variability in offshore export of meltwater is tightly related to variability in wind forcing. The new insight that meltwaters originating from the west and east coasts have different fates indicates that future changes in mass loss rates and surface runoff will probably impact the ocean differently, depending on their Greenland origins.

Greenland ice sheet (GrIS) mass losses have accelerated during recent decades[4], having nearly tripled since the 1950s[5]. GrIS melting reached its highest extent in more than a century during the summer of 2012[6], setting new records in many of the years of the past decade[7]. GrIS runoff from surface melting, accounting for at least half of the total mass loss (the remainder being ice discharge)[8], has increased substantially over recent decades in association with atmospheric warming[9].

Understanding the fate of GrIS meltwater runoff is important because freshwater input can strongly influence ocean circulation, vertical stability and sea ice formation[10], and biogeochemical processes[2]. Recent modelling studies have reconstructed meltwater fluxes from Greenland[11]. Identifying the transport pathways of meltwater in the ocean and understanding their controls are crucial in light of predictions that meltwater fluxes will increase even further as a result of warming trends. At the present rate, meltwater runoff from Greenland is predicted to more than double by the end of this century[12].

Here, we use a decade-long ocean model[13] simulation to investigate the fate of surface meltwater runoff from the GrIS in the Labrador Sea (Fig. 1). Tracer releases are used to track West and East Greenland meltwater runoff (WGMR and EGMR, respectively) in 2008–2012, revealing that the fate of surface meltwater runoff depends on where it is delivered to the ocean from Greenland (Fig. 2). Most notably, EGMR extends substantially farther into the northern Labrador Sea than WGMR. This results in the volume of freshwater from EGMR (Fig. 3b) transported towards the northern Labrador Sea being 3–25 times larger than the volume from WGMR (Fig. 3a). This is surprising, considering that the volume of surface meltwater runoff introduced along West Greenland was either comparable (2008–2010) or larger (2011–2012) than along East Greenland (Fig. 4a). The differences become even clearer when the volume of meltwater transported offshore is normalized by the volume of meltwater introduced along the east or west coasts. Only 15–20% or less of the WGMR reaches section 3 in the northern Labrador Sea (see Fig. 2c for location), and percentages decrease further with offshore distance to less than half of the values near the coast (Fig. 3c). By contrast, ~50% of the EGMR reaches section 12, midway between Greenland and Canada, in three of the five years considered (Fig. 3d), and percentages in those years decrease very slowly with distance from shore, revealing that EGMR is transported into the northern Labrador Sea very efficiently.

Large interannual variability in offshore transport of EGMR and WGMR is observed, but it does not correspond to runoff variability. Two years with low runoff in the 2008–2012 period, 2008 and 2009 (Fig. 4a), were characterized by high transport of meltwater towards the northern Labrador Sea (Fig. 3), whereas the two years with the largest runoff, 2010 and 2012, were characterized by weak offshore transport. Interannual variability in eddy kinetic energy off West Greenland[14] (Supplementary Fig. 1) does not correspond to interannual variability in offshore transport of EGMR and WGMR either, suggesting that interannual variability in mesoscale activity by itself cannot account for the observed interannual variability in offshore export of meltwater. Winds can play a crucial role in controlling cross-shelf transport of low-salinity waters in coastal systems[15]. Whereas upwelling-favourable winds (that is, southeastward along West Greenland) induce offshore transport in the surface layer, downwelling-favourable winds (that is, northwestward) induce onshore transport. Increases or decreases in cumulative alongshelf wind stresses[16] along West Greenland indicate predominant downwelling- or upwelling-favourable winds, respectively (Fig. 4b). During summer, when meltwater runoff is high, winds are downwelling favourable on average. This contributes to constraining the meltwater near the West Greenland coast where it can be transported northwards into Baffin Bay by coastal currents.

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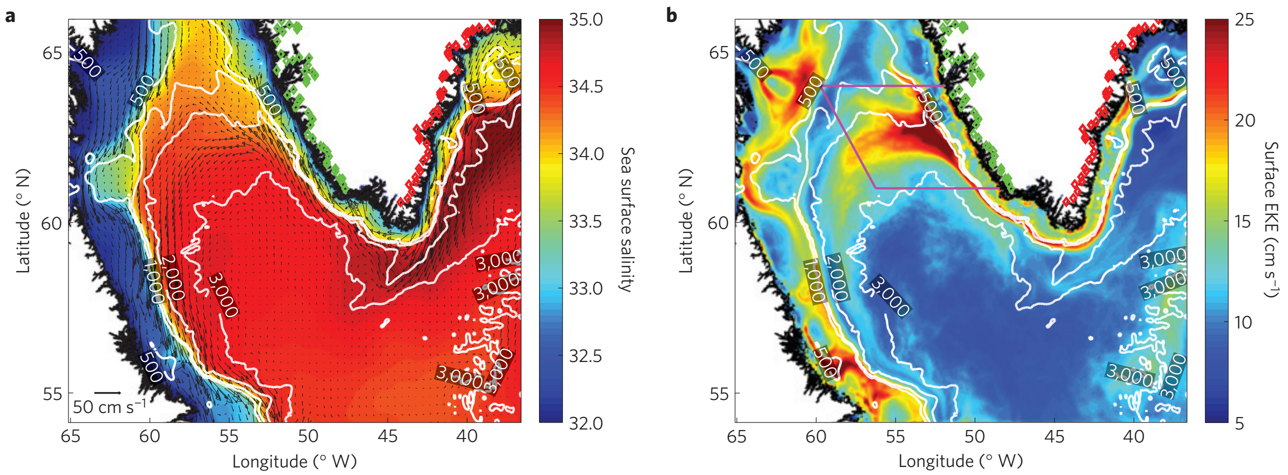

Figure 1 | Mean circulation. a, Sea surface salinity (colour map) and surface currents (vectors) averaged from 2008 to 2012. The 500, 1,000, 2,000 and 3,000 m isobaths are shown in white. Green and red symbols show the locations of West and East Greenland meltwater runoff inputs, respectively. **b**, Mean (2008–2012) surface eddy kinetic energy (EKE) cast as a speed, $(u^2+v^2)^{1/2}$, where u and v are the horizontal components of the surface velocity after subtracting the respective means[14]. The magenta box shows the region where the time series of EKE anomaly was computed (Supplementary Fig. 1).

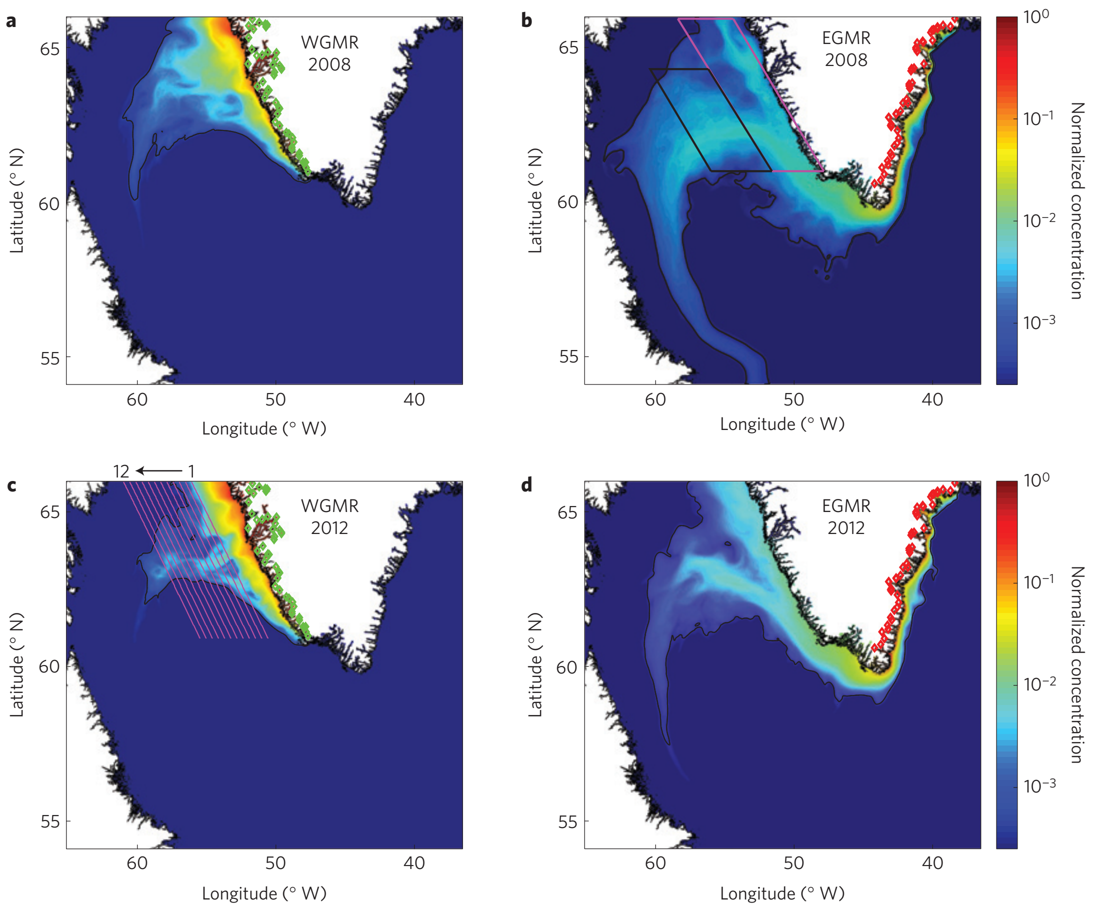

Figure 2 | Transport pathways of meltwater in the ocean around Greenland. Surface tracer concentration averaged from June to December. Tracer was released with WGMR (**a**,**c**) and EGMR (**b**,**d**) in 2008 (**a**,**b**) and 2012 (**c**,**d**). Sections used to quantify meltwater fluxes are shown in **c**. Black contours show an average dye concentration of 4×10^{-4}. Green and red symbols show locations of WGMR and EGMR inputs, respectively. The magenta box in **b** shows the region where cumulative alongshore wind stresses are computed and where model outputs are compared with National Oceanographic Data Center (NODC) observations. The black box shows the region on the northern Labrador Sea where salinity and vertical density gradient anomalies are calculated (Fig. 4).

This is consistent with maximum concentrations of freshwater from Greenland being found in Baffin Bay[17], where it can influence water exchange with the Arctic Ocean[18]. However, wind forcing is characterized by large interannual variations. In 2008 and 2009, when offshore transport of meltwater was strongest (Fig. 3), predominant downwelling-favourable winds lasted only until July

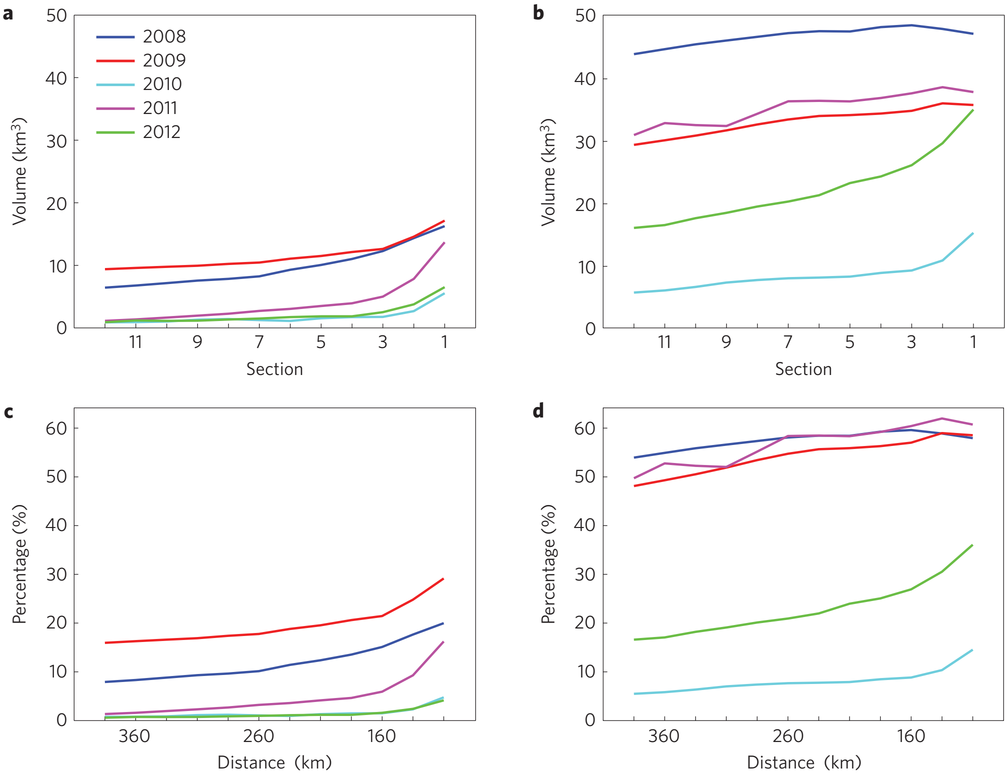

Figure 3 | Offshore export of meltwater in the Labrador Sea. Cumulative transport of meltwater into the northern Labrador Sea by 31 December of 2008–2012 across the 12 sections shown in Fig. 2c. **a**,**b**, Volumes of freshwater from WGMR (**a**) and EGMR (**b**). **c**,**d**, Percentage of freshwater from WGMR (**c**) and EGMR (**d**) (that is, normalized by the amount of meltwater introduced into the ocean along the West and East Greenland coasts) transported offshore across the sections.

(Fig. 4b). From August to October, coastal winds were upwelling favourable (Fig. 4b), which facilitated the offshore transport of meltwater. In 2010 and 2012, winds were downwelling favourable during the entire melting season, explaining why those two years were characterized by small offshore transport of meltwater (Fig. 3) despite the large runoff (Fig. 4a).

Analysis of tracers in 2011, when offshore transport was large for EGMR (as large as in 2008/2009; Fig. 3d), but low for WGMR (almost as low as in 2010/2012; Fig. 3c) further supports this interpretation. Winds off West Greenland were strongly downwelling favourable until mid-September, but strongly upwelling favourable after that (Fig. 4b). As most of the WGMR entered the ocean in July–August (Fig. 4a), it experienced downwelling-favourable winds, which is consistent with weak offshore transport (Fig. 3a,c). The situation is different for EGMR, however. Even though freshwater from EGMR is also introduced into the ocean at approximately the same time (Fig. 4a), it takes about 2–2.5 months for it to be transported around the southern tip of Greenland into the West Greenland Current (Supplementary Fig. 2). By that time, winds in 2011 had reversed, becoming predominantly upwelling favourable (Fig. 4b), which is consistent with strong offshore transport of EGMR (Fig. 3b,d). The reversal in predominant wind direction in mid-September resulted in a strong difference in the fate of the freshwater from WGMR and EGMR in 2011. Similar wind reversals have occurred 20–25% of the time since 1979 (Supplementary Fig. 3).

The westward transport of meltwater results in a decrease in salinity offshore compared to a scenario in which no meltwater runoff is considered (Fig. 4c), particularly in 2008–2009 when enhanced export occurred. The salinity decrease offshore due to meltwater input is about 20% of the seasonal decrease detected in observations near the coast due to all sources of freshwater (for example, meltwater, freshwater from the Arctic transported by the East and West Greenland Currents; Supplementary Fig. 4c). The vertical density gradient in the top 100 m also increases significantly offshore in those years (Fig. 4d), by 40% in 2008 and by as much as 100% during a short pulse in 2009. Because glacial runoff is predicted to increase substantially in the coming decades[12], we explore an idealized scenario in which meltwater runoff is doubled compared to present conditions. In that case, the decrease in salinity and the increase in vertical density gradients offshore are also largely enhanced, more than doubling in 2008–2009 compared to the anomalies produced under present conditions (Fig. 4c,d). The additional meltwater leads to a reduction in mixed layer depth near the West Greenland coast (Supplementary Fig. 5), which results in the wind energy being trapped in a thinner surface Ekman layer[15] and in stronger offshore velocities, leading to enhanced offshore transport. As such, doubling meltwater input results in more-than-double increases in salinity and stratification anomalies away from the coast. The period with large anomalies in the northern Labrador Sea also increases, persisting further into winter, especially in 2008 (Fig. 4c,d).

Our analysis reveals that coastal winds play a crucial role in the fate of GrIS meltwater runoff. Other factors are also likely to be important, including mean circulation patterns and eddy activity. Eddies can efficiently transport coastal water offshore[19]. If meltwater reaches the area of high mesoscale activity observed in the region[14] (Fig. 1b), then eddies can contribute to exporting the low-salinity waters farther offshore into the northern and central Labrador Sea[19,20]. The mean currents at 100–150 km from shore turn westwards around 62°–63° N[21] (Fig. 1a), indicating that if meltwater reaches that region, it can be further transported offshore. These may explain the large differences in offshore transport observed between WGMR and EGMR (Figs 2 and 3). WGMR is typically

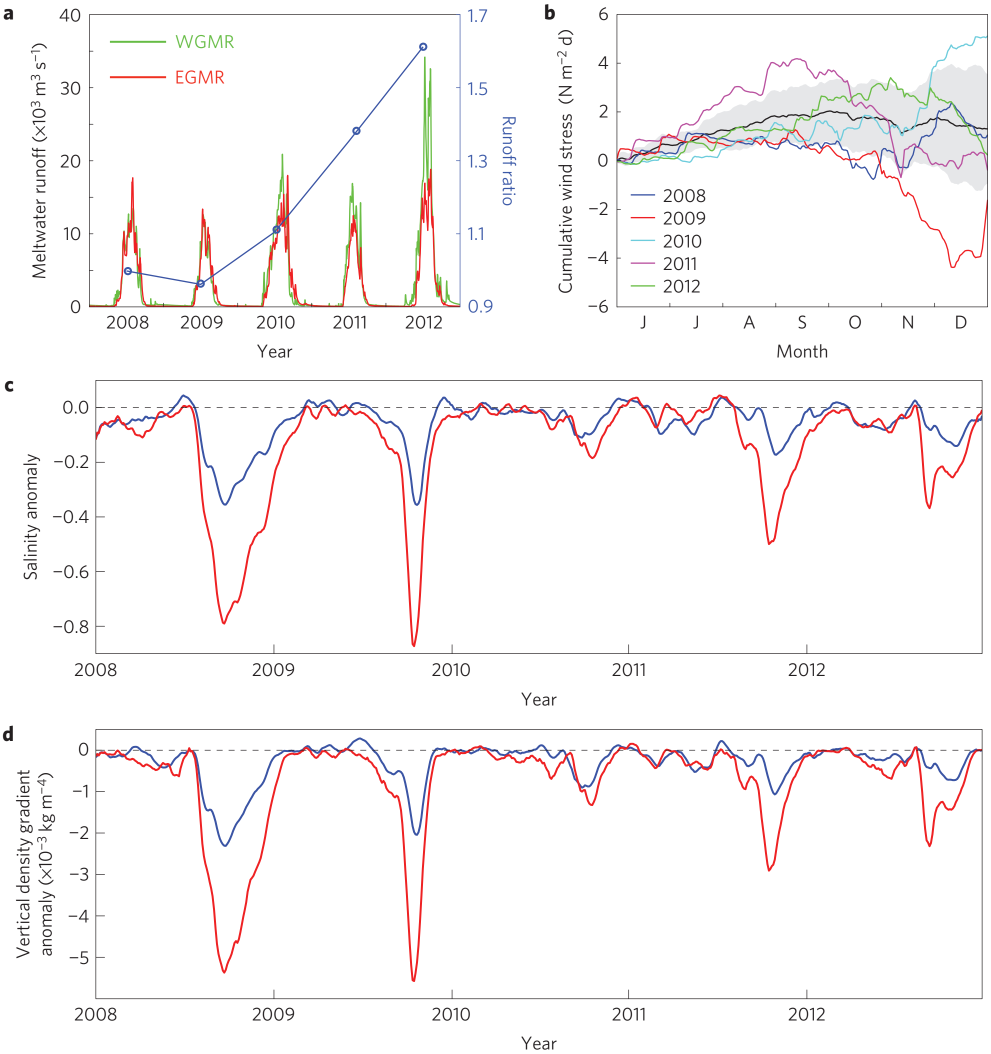

Figure 4 | Interannual variability in the Labrador Sea. a, GrIS meltwater runoff. **b**, Cumulative alongshore wind stress averaged along West Greenland (magenta box in Fig. 2b) for the months June to December. Black line and shaded grey show mean ±1 s.d. for 2003–2012. **c**, Salinity anomaly in the northern Labrador Sea (black box in Fig. 2b) due to meltwater, defined as the difference between simulations with and without meltwater input (blue), and between simulations with double meltwater input and without meltwater input (red). **d**, Same as **c**, but for the vertical density gradient in the top 100 m.

delivered to the ocean from inside fjords, and therefore would need to be transported offshore by some mechanism (for example, winds) before it can reach the region where eddies and/or mean circulation can transport the low-salinity water farther away from the coast. However, coastal winds are downwelling favourable on average (Fig. 4b), acting against that transport. EGMR is also introduced into the ocean via fjords, but it is then transported for several hundred kilometres in the East Greenland Current before reaching West Greenland, allowing the band of low-salinity water to widen (for example, owing to mixing, flow–topography interactions; compare WGMR and EGMR distribution at 61° N along West Greenland, Fig. 2). That widening allows low-salinity water to reach the region of increased mesoscale activity where the mean circulation is deflected offshore (Fig. 1), which would lead to further offshore transport.

Model results reveal surprisingly large differences in the fate of freshwater from EGMR and WGMR in the ocean surrounding Greenland. This discrepancy can have important biogeochemical implications, especially if EGMR and WGMR have different chemical compositions or seasonal timing. Most of the freshwater from WGMR is transported northwards into Baffin Bay. Given enough time, a fraction of such meltwater runoff may be transported by the mean ocean circulation around Baffin Bay and eventually back into the western Labrador Sea[22]. Most of the meltwater being transported directly into the Labrador Sea is introduced into the ocean along East Greenland, however, implying a much shorter transit time of a few months. This indicates that up to 60% of the EGMR reaches the northern Labrador Sea by fall/early winter, where it can affect surface stratification. Our idealized simulations representing future conditions reveals that further increases in meltwater runoff, especially along East Greenland, will probably lead to enhanced freshwater fluxes towards the northern Labrador Sea, so that doubling meltwater input results in more-than-double increases in salinity and stratification anomalies offshore. The increased anomalies may extend further into winter, with possible implications for hydrography and vertical stability. Whereas many studies have quantified chemical fluxes (for example, iron[2], organic carbon[23], phosphorus[24]) in meltwater runoff from West Greenland, long-term studies along East Greenland are less common. Our results suggest that nutrients introduced into the ocean with WGMR will probably be transported northwards into Baffin Bay, whereas the northern Labrador Sea will be more influenced by chemical constituents introduced with EGMR. Because nutrient input associated with glacial runoff can affect primary productivity[25], and nutrient yields can vary substantially between Greenland glaciers[24], constraining fluxes from East Greenland glaciers will be important to quantify the potential impacts of increased runoff on biogeochemical processes in the Labrador Sea.

Although GrIS meltwater runoff has been increasing in both West and East Greenland (Supplementary Fig. 6), the largest increase in recent years occurred mostly along the west coast[6,9]. EGMR, which was shown here to have a more direct impact on the northern Labrador Sea, was characterized by comparatively smaller interannual variability recently (Fig. 4a). Knowing whether this pattern will continue, or if runoff along East Greenland will also accelerate in the future, will be crucial to understand the potential impacts of Greenland ice sheet melting on ocean processes.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

H.L. and R.M.C. conceived and designed the research; H.L. ran the model; A.K.R., M.T., A.B., P.L.Y. and T.L.M. contributed materials/analysis tools; H.L. and R.M.C. analysed the data/model outputs and wrote the paper; all authors commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.M.C.

Competing financial interests

The authors declare no competing financial interests.

Methods

The ocean modelling effort builds on a previous implementation of the Regional Ocean Modeling System (ROMS)[13] to the Labrador Sea and southern Greenland[14,26]. The model has a horizontal resolution of 2.5 km with 30 vertical terrain-following layers. Vertical mixing is parameterized according to the Large/McWilliams/Doney scheme. Initial and boundary conditions are obtained from the Simple Ocean Data Assimilation (SODA 2.2.4) reanalysis[27], which has been shown to produce improved results in this implementation compared to other reanalyses[26]. A modified radiation condition coupled with nudging to the reanalysis is prescribed along the boundaries[14,26]. ROMS is additionally forced by daily surface wind stresses and heat fluxes from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-interim reanalysis[28]. Surface heat fluxes are employed with nudging towards NOAA extended sea surface temperatures to avoid model drifts[26].

The regional climate model Modèle Atmosphérique Régional (MAR) coupled to the 1-D Surface Vegetation Atmosphere Transfer scheme Soil Ice Snow Vegetation Transfer (SISVAT)[29] is used to estimate ice sheet surface meltwater runoff. To calculate time series of meltwater fluxes into the ocean at the major input locations, MAR runoff is integrated for 108 ice sheet catchments upstream of each input loci. Catchment areas and their output locations are determined by using a high-resolution ice sheet surface elevation model[30]. Average MAR runoff (266 ± 66 GT yr^{-1}) over the entire ice sheet is comparable to runoff from the Regional Atmospheric Climate Model with ECMWF forcing (282 ± 62 GT yr^{-1})[12]. Idealized simulations with no meltwater input or with double input are also pursued. Although ice discharge from marine terminating glaciers of the GrIS also provides freshwater input to the ocean, those fluxes are most substantial outside or at the edges of our study area[8], and were not included here. Two different passive tracers with unit concentration are released with meltwater runoff along the West (west of 47.6° W and south of 66° N) and East (east of 44.2° W and south of 66° N) Greenland coasts (WGMR and EGMR, respectively; see Fig. 2), so that the amount of the tracers released is proportional to the local freshwater fluxes. The total volume of meltwater passing through 12 alongshore sections shown in Fig. 2c is quantified for each year.

Although it would have been consistent to force ROMS with MAR winds, the MAR domain covers only a small fraction of the ocean model domain. Detailed analysis reveals that ERA-Interim and MAR winds are highly correlated and consistent to each other in the study region. ROMS was run from 1999 to 2012, and the first four years were discarded from analyses (model spin-up). Here, we focused only on 2008 to 2012, which included anomalous events of meltwater runoff and wind forcing. Because SODA 2.2.4 reanalysis is available only until 2010, we extended the model run to 2012 by repeating the 2010 boundary conditions for the following two years.

The model implementation builds on a previous investigation in which the circulation and surface eddy kinetic energy were validated with observed altimetry data[14,26]. Additional model–data comparisons are shown in Supplementary Fig. 4. Because few *in situ* observations are available, model results are compared with historical observations from the National Oceanographic Data Center (NODC). Observed sea surface salinity (SSS) from 1950 to 2013 is shown in Supplementary Fig. 4a and the modelled SSS from 2003 to 2012 is shown in Supplementary Fig. 4b. We use data since 1950 because of the relatively small number of observations available for 2003–2012. A band of low SSS broadening to the northwest is observed along the West Greenland coast, associated with freshwater input during summer. Surface water farther from the coast is much saltier, both in the observations and in the model. Time series of monthly averaged salinity along the coast (inside the magenta box in Fig. 2b) reveal that the model is able to capture the freshening observed during summer (Supplementary Fig. 4c). Modelled salinity before July and after October is overestimated by 0.1–0.4, possibly because the SODA reanalysis used as the boundary condition is characterized by slightly warmer and saltier conditions compared to the observed mean state[26]. Model results also agree well with time series of potential temperature at depth (1,000–1,500 m) at the central Labrador Sea obtained by Argo profiles (Supplementary Fig. 4d), capturing the observed warming trend during the past decade and the rapid drops in temperature during the winters of 2008 and 2012. This suggests that the model can capture the processes characterizing not only the input of meltwater near the coast, but also those related to large-scale circulation patterns in the study region[14,26]. The model–data discrepancy increases slightly (by 0.05 °C) after 2011 (Supplementary Fig. 4d), presumably because SODA reanalysis data are not available after 2010 (that is, boundary conditions were repeated after that).

Code availability. Model codes are available at www.myroms.org and www.cryocity.org/mar-explorer.

Data availability. The data/reanalysis that support the findings of this study are publicly available online at www.nodc.noaa.gov, www.argo.ucsd.edu and www.ecmwf.int/en/research/climate-reanalysis/era-interim.

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