Emerging impacts of enhanced Greenland melting on Labrador Sea dynamics

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Abstract

Freshwater input from Greenland ice sheet melt has been increasing in the past decades from warming temperatures. To identify the impacts from enhanced meltwater input into the subpolar North Atlantic from 1997–2021, we use output from two nearly identical simulations in the eddy-rich model VIKING20X (1/20°) only differing in the freshwater input from Greenland: one with realistic interannually varying runoff increasing in the early 2000s and the other with climatologically (1961–2000) continued runoff. The majority of the additional freshwater remains within the boundary current enhancing the density gradient towards the warm and salty interior waters yielding increased current velocities. The accelerated boundary current shows a tendency towards eddy shedding into the Labrador Sea interior. Further, the experiments allow to attribute higher stratification and shallower mixed layers southwest of Greenland and deeper mixed layers in the Irminger Sea, particularly in 2015–2018, to the runoff increase in the early 2000s.

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Key Points:

- The West Greenland Current (WGC) freshens and cools with the observed recent increase in meltwater runoff from Greenland
- The density gradient across the boundary current intensifies, strengthening the WGC and increasing local eddy formation
- Deep mixing of meltwater at shallower depths in the Labrador Sea contributes a shift in deep convection into the Irminger Sea (2015–2018)

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Abstract

Freshwater input from Greenland ice sheet melt has been increasing in the past decades from warming temperatures. To identify the impacts from enhanced meltwater input into the subpolar North Atlantic from 1997–2021, we use output from two nearly identical simulations in the eddy-rich model VIKING20X (1/20°) only differing in the freshwater input from Greenland: one with realistic interannually varying runoff increasing in the early 2000s and the other with climatologically (1961–2000) continued runoff. The majority of the additional freshwater remains within the boundary current enhancing the density gradient towards the warm and salty interior waters yielding increased current velocities. The accelerated boundary current shows a tendency towards eddy shedding into the Labrador Sea interior. Further, the experiments allow to attribute higher stratification and shallower mixed layers southwest of Greenland and deeper mixed layers in the Irminger Sea, particularly in 2015–2018, to the runoff increase in the early 2000s.

Plain Language Summary

Global warming has accelerated the melting of the Greenland ice sheet over the past few decades resulting in enhanced freshwater input into the North Atlantic. The additional freshwater can potentially inhibit deep water formation and have future implications on ocean circulation. To determine the impact from Greenland melt, we compare two high-resolution model experiments all with the same forcing but differing input of Greenland freshwater fluxes from 1997–2021. We find that in the experiment with realistically increasing Greenland meltwater, the water becomes fresher and cooler along the continental shelf and boundary of the subpolar gyre. The density difference between the shelf and interior increases with more freshwater, resulting in faster West Greenland Current speeds and enhanced eddy formation. Deeper mixed layers are found in the eastern Irminger Sea, particularly in 2015–2018. From 2009–2013, there were shallower mixed layers in the Labrador Sea where less Greenland meltwater was mixed downwards and spread eastward, causing mixed layers to deepen in the Irminger Sea.

1 Introduction

The Greenland ice sheet has been losing mass over the last couple of decades as a result of global warming (Hanna et al., 2008; Fettweis et al., 2011; Bamber et al., 2018). With an increasing amount of freshwater input, there has been interest in the impact it will have on circulation in the subpolar North Atlantic (SPNA), particularly whether additional freshwater will increase stratification and reduce deep water formation, which could weaken the Atlantic Meridional Overturning Circulation (AMOC) (Rahmstorf et al., 2015; Bakker et al., 2016; Böning et al., 2016; Swingedouw et al., 2022). Freshwater from Greenland melt will first appear in the East and West Greenland Currents (EGC/WGC) on top of Arctic sourced fresh Polar Water contained in these boundary currents (de Steur et al., 2009, 2018). Both the EGC and WGC consist of two surface intensified double current cores with a coastal current and outer slope current just beyond the shelfbreak (Bacon et al., 2002; Håvik et al., 2017; Sutherland & Pickart, 2008; Le Bras et al., 2018; Myers et al., 2009; Pacini et al., 2020; Gou et al., 2021). We will use the term boundary current to address both cores together as one system. The major current pathways are shown in Figure 1a.

The EGC is observed to be fairly coherent with minimal freshwater export along east Greenland; strong alongshore winds constrain the majority of fresh and cool water near the shelf (Sutherland & Pickart, 2008; Le Bras et al., 2018; Duyck et al., 2022; Schiller-Weiss et al., 2023). Along southeast Greenland at Cape Farewell, tip jets, northeasterly winds, and a retroflection can export freshwater into the central Irminger Sea (Duyck et al., 2022; Holliday et al., 2007). The WGC consists of near surface buoyant and fresh waters with warmer and salty Irminger water at depth (Gou et al., 2022; Myers et al., 2007; Fratantoni & Pickart, 2007; Pacini et al., 2020). There are differing pathways freshwater is transported by the WGC, it can flow northward into Baffin Bay or cyclonically around the Labrador basin (Pacini et al., 2021; Gou et al., 2021). Freshwater from the WGC can be fluxed into the central Labrador Sea via offshore Ekman transport (Luo et al., 2016; Castelao et al., 2019; Schulze Chretien & Frajka-Williams, 2018) and eddies (Lilly et al., 2003; Katsman et al., 2004; Rieck et al., 2019; Pacini & Pickart, 2022). The Labrador and Irminger Sea will both be referred to as LAB and IRM throughout the manuscript.

Eddies that are shed into the LAB from the boundary current have different origins. Irminger Rings are formed from steep topographic differences in the slope south of Cape Desolation (CD) (Lilly et al., 2003; Bracco et al., 2008; Luo et al., 2011; de Jong & de Steur, 2016; Rieck et al., 2019). Boundary current eddies are generated near the shelf in the WGC and Labrador Current via baroclinic instabilities which intensify in winter when currents strengthen (Katsman et al., 2004; Chanut et al., 2008; Rieck et al., 2019). Eddies have been observed to play a significant role in determining the magnitude and location of deep convection, restratification, and preconditioning processes by transporting heat and freshwater into the interior LAB and IRM (Gelderloos et al., 2011; Chanut et al., 2008; Rieck et al., 2019). An eastward shift in deep convection was observed from 2015–2018 (Zunino et al., 2020; Piron et al., 2017; Rühs et al., 2021), which Rühs et al. (2021) hypothesized may partially be attributed to accelerated Greenland melting. As more freshwater enters the boundary currents, it is important to understand and identify associated hydrographic and potential dynamical changes.

In this study, we investigate the impact of Greenland freshwater input between two nearly identical high-resolution, eddying ocean/sea-ice model runs from 1997–2021 but with differing Greenland freshwater fluxes (FWFs). We break down the question for an observable imprint by enhanced Greenland meting onto the ocean into the following subtopics: (1) hydrographic changes i.e. in near-surface salinity and temperature (2) dynamical changes i.e. changes in density and its influence on boundary current strength and eddy formation, and (3) changes in mixed layer depth (MLD) with a particular focus on additional freshwater contributing to the eastward shift of deep convection.

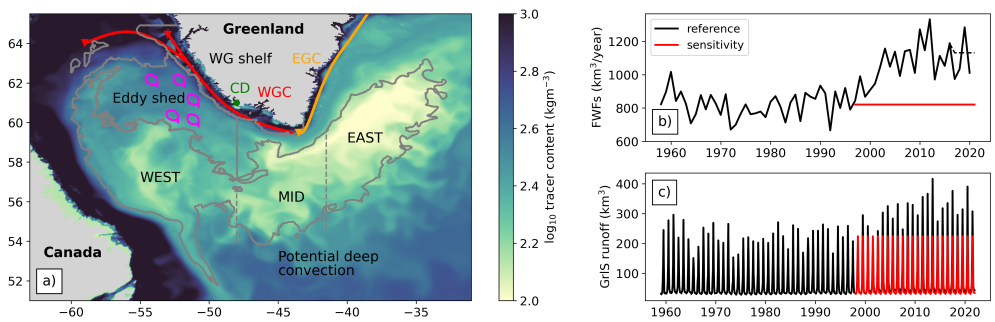

Figure 1. (a) Snapshot of passive tracer integrated over the top 200m and schematic of surface currents. The three gray contours show the West Greenland shelf, eddy shedding region (eddies marked by fuchsia rings), and the area of potential deep convection split into three subregions: LAB (WEST), south of Cape Farewell (MID), and IRM (EAST). Cape Desolation (CD) location marked in green. (b) Total, annual FWFs from Greenland runoff from 1960–2021. (c) Monthly varying FWFs. Black line shows interannually varying FWF of REF, dashed line shows 2012–2016 mean; the red line shows the reduced, climatological FWF from SENS.

2 Ocean Model Experiments

We compare two nearly identical model simulations from the ocean/sea-ice general circulation model configuration VIKING20X (Biastoch et al., 2021) (model details described in Supporting Information): one including the observed increase in Greenland runoff (hereafter referred to as ”reference”, short REF) and a ”sensitivity” experiment (SENS), where the Greenland FWFs is reduced to the climatology of 1961–2000. In REF Greenland FWFs are interannually varying with an increasing trend shown in the total annual FWFs (black line of Figure 1b), based on (Bamber et al., 2018; Slater et al., 2021). The FWFs are monthly varying with a prominent seasonal cycle (Figure 1c) and are released at the surface and coastline, tagged by an accumulated passive tracer (Figure 1a). Greenland FWFs from Bamber et al. (2018) do not extend beyond 2016 and runoff in the JRA55-do forcing data set is continued by maintaining a daily varying climatology of 2012–2016 (Tsujino et al., 2018). In order to include a fair representation of the years after 2016, in particular the record runoff year 2019 (Tedesco & Fettweis, 2020), we computed a scaling factor for the JRA55-do Greenland runoff after 2016 based on the study of Slater et al. (2021), which provides satellite-derived measurements of Greenland runoff variability. While the scaling is based on the total Greenland runoff, the factor is applied to local FWFs per model grid cell to generate the forcing, i.e. the spatial pattern of the Greenland FWF is still tied to the 2012–2016 mean. SENS differs from the reference run in Greenland FWFs here represented as daily climatology from 1961–2000 (red line representing the suppressed FWFs in Figure 1b, c).

3 Results

The following analysis focuses on significant changes between REF and SENS. We first start by investigating significant sea surface salinity (SSS) and temperature (SST) differences, then changes in the West Greenland boundary current strength, followed by differences in eddy kinetic energy (EKE) to investigate the potential for enhanced eddy formation from changes in the boundary current. Lastly we attribute a deepening of mixed layers in the IRM to the enhanced FWF in REF (particularly in 2015–2018) and discuss the mechanisms leading to a contribution by Greenland meltwater to the eastward shift of deep convection in recent years.

3.1 Surface freshening and cooling

The first imprint of enhanced Greenland FWFs in the hydrography appears along the Greenland shelf. We focus on the last 20 years of the simulation (2002 - 2021) to allow for the additional freshwater to quasi-equilibrate (the linear trend in total Greenland FWF applied to REF is nearly zero over these two decades). We focus on annual means and compute differences (REF minus SENS) showing a significant freshening and cooling in SSS and SST particularly along the continental shelves (Figure 2a, b). Freshening and cooling appear throughout the year, with fresher water near the shelf in summer clearly associated with the seasonal peak in Greenland runoff (Bamber et al., 2018) (Figure S1a, c).

Significant areas of the SSS difference, purple in Figure 2a implying lower salinities in REF compared to SENS, are found primarily in the WGC, the LAB shelf, and eddy shedding region. We define the WGC boundaries by the 1000 m isobath and the eddy shedding boundary between the 1000 and 2000 m isobath (Figure 1a). The southern boundary is limited by the potential deep convection area (pDCA), defined as any grid point where MLDs exceed $z_{critical}$ = 1000 m at least once (Rühs et al., 2021) between 2002–2021 (Figure 1a). Statistical significance is computed from bootstrap resampling (Bertino et al., 2003) where significant areas are defined when the difference between the resampled means are larger than the total standard deviation of the two bootstrapped runs.

The coolest SSTs occur near the shelves and eddy shedding region where the LAB's shelf boundary exhibits anomalously cooler SSTs in REF (Figure 2b). The strong cooling around the northwest LAB boundary is associated with a greater extent of winter sea ice in REF (Figure S1a, c, e) attributed to local sea-ice formation and export from Baffin Bay (Våge et al., 2009; Kwok, 2007). (Deser et al., 2002) also observed that sea ice formation lagged changes in salinity along the WGC by 8 months i.e. summer melting affects the LAB's northern sea ice extent.

2010 and 2012 were two years of exceptional Greenland runoff (Tedesco et al., 2011; Hanna et al., 2014) (Figure 1b). This is most evident in the WGC where both REF and SENS decrease in salinity from 2010–2012 (Figure 2c). Although 2019 was a year of anomalous Greenland melt, the majority of melt occurred further northwest of the ice sheet (Tedesco & Fettweis, 2020), thus the salinity decrease is less than in 2010 and 2012. 2012 remaining the year of strongest Greenland melt on record from higher humidity and air temperature over the ice sheet (Tedesco & Fettweis, 2020).

REF has lower annual mean salinities than SENS in the WGC where the salinities show a larger spread between the two runs beginning in 2004, a few years after the rapid increase in Greenland FWFs from 2000 onwards (Figure 1b). The eddy shedding region exhibits less of a spread in SSS annual means than found in the WGC. Interestingly, the strong reduction in SSS begins in 2011 rather than 2010, a year with record runoff. Alongshore winds were downwelling favorable in the winter of 2010 following the exceptional summer runoff and hence offshore transport of relatively fresh waters was even less than in 2011 (Figure S2) (Myers et al., 2021), highlighting the importance of wind forcing over runoff for freshening events offshore the WGC.

The VIKING20X-JRA OMIP hindcast run from which both REF and SENS are branched off in 1997, shows quasi multi-decadal variability with lower salinities in the 1970s and 2000s and higher salinities in the 1980s–1990s. The sharp decrease in salinity in both the WGC and eddy shedding region in 1969 is identified as the Great Salinity anomaly from 1968–1982 (GSA'70s) resulting from anomalous Arctic export via Fram Strait (Dickson et al., 1988; Belkin et al., 1998). In REF, the period of 2010–2012 attributed to exceptional Greenland runoff reaches even lower SSS values than the GSA'70s emphasizing the significance that Greenland FWFs has on the boundary current.

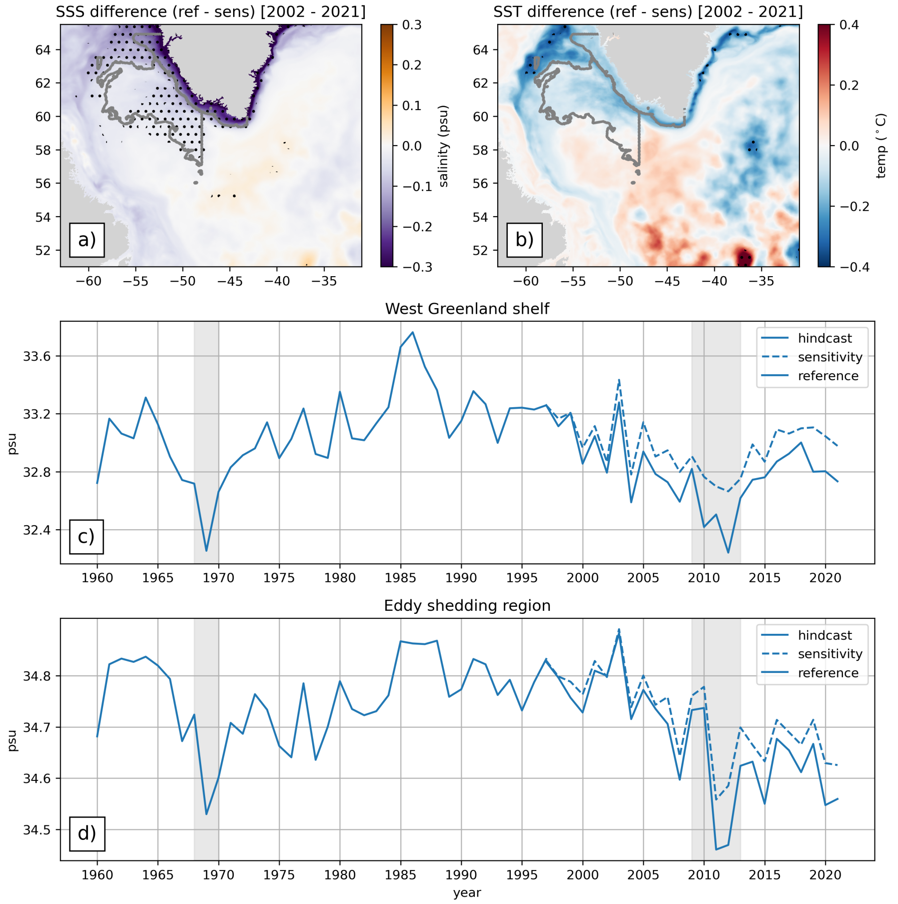

Figure 2. (a) Mean surface salinity (2002–2021) response (REF minus SENS) and (b) mean sea surface temperature difference. Black stippling indicating significant areas. Gray contours mark the West Greenland shelf and eddy shedding region. (c) Annual mean SSS over the West Greenland shelf. (d) Annual mean SSS over the eddy shedding region. The solid line is based on the hindcast simulation (1960–1996) and from REF in 1997–2021; the dashed line represents SENS. Gray vertical bars indicate the GSA'70s and 2010–2012 years of strong Greenland melt.

3.2 Strengthened boundary current

The enhanced Greenland runoff over the recent decades contributes to the fresh polar watermass carried by the Greenland boundary current system—with the shown near-surface cooling contributing a slight but less effective density offset (Figure S1e, f). The density decrease on the shelf intensifies the horizontal gradient towards the denser interior LAB and strengthens the WGC via thermal wind balance (Gou et al., 2022; Katsman et al., 2004). To investigate these changes in the boundary current system, we take an exemplary cross section at OSNAP West (Lozier et al., 2019) to obtain the velocity structure of the WGC in REF (Figure 3a). The boundary current consists of two current cores both reaching velocity magnitudes up to 0.5 m/s: the West Greenland coastal current (WGCC) and just off the shelfbreak, the slope current. The WGCC contains the most polar water along with traces of Greenland meltwater (Lin et al., 2018; Pacini et al., 2020; Gou et al., 2022). The slope current is adjacent and lies above the saltier and warmer Irminger Current (Fratantoni & Pickart, 2007; Myers et al., 2009). We isolate the surface intensified WGCC and slope current by taking the top 100 m and northwestward velocities only (black boxes in Figure 3a). We sample the WGC system by selecting only the top 100 m as a conservative choice to focus on the fresh and fast WGC (Gou et al., 2021).

The slope current (Figure 3b, orange lines) has greater annual mean velocities from 2002–2021 on average than the WGCC (blue lines) and appears to increase while the WGCC shows stronger interannual variability. At OSNAP West, slope current speed has an increasing trend over the last two decades, also found by (Gou et al., 2022) south of Fylla Bank. Both the mean WGCC and slope current velocities are greater in REF (solid lines) than in SENS, particularly in 2011 where the speeds deviate more (Figure 3b). While the increase in REF is relatively small, the bootstrapped means are statistically significant where the resampled reference mean velocity for both currents are greater than the 90^{th} percentile of the resampled SENS velocities. As the spread increases towards 2021, we speculate that this signal will emerge more clearly over the next years. Note that in contrast to earlier hosing and freshwater-release experiments, the much smaller observed increase in Greenland FWF studied here can only drive a slight increase in the boundary current speed.

Nevertheless, at OSNAP West there is a significantly faster flow speed increasing the potential for local instabilities causing more eddies to be shed into the interior (Gou et al., 2023; Chanut et al., 2008; Katsman et al., 2004). We thus analyze the EKE after discussing the thermal wind balance effect. The surface density gradient between the shelf and interior increases due to enhanced runoff, resulting in a faster boundary current. To investigate this, we evaluate a "cumulative correlation" formed by the sum of the Pearson's correlation coefficient (capped at 1.0) between the WGCC and slope current mean speed at OSNAP West, CD, and Fylla Bank and the horizontal density gradient at the surface in REF (Figure 3c, d). The current structure and correlation map per cross section are discussed further in Supporting Information Text and Figure S3.

The WGCC shows a band of higher positive cumulative correlations surrounding the Greenland coast (Figure 3c), which illustrates the strong link between a strengthening of the current speed and an increase in the density gradient across the shelf break. In addition to the strengthening of the density gradient, the dipole pattern created by a band of negative correlations just offshore, suggests an inshore movement of the sharp density gradient following the shelf break in periods with intensified WGCC flow speeds. In contrast, the cumulative correlation between the slope current and the density gradient shows a less confined pattern (Figure 3d), where a patch of positive cumulative correlations is found in the northeast LAB and the eddy shedding region.

We argue that the greater area of positive correlations with the slope current is driven by an enhanced eddy activity during increased flow speed along the shelf slope. Since horizontal density gradients are computed per model grid cell, the sharp fronts of mesoscale eddies dominate an area of otherwise smaller horizontal density fluctuations. The relatively strong correlation with the accelerating slope current (Figures 3b, d) hints at growing eddy activity in this region. Does this mean that EKE is enhanced in REF over SENS, i.e. is there a change in eddy activity related to enhanced Greenland FWFs?

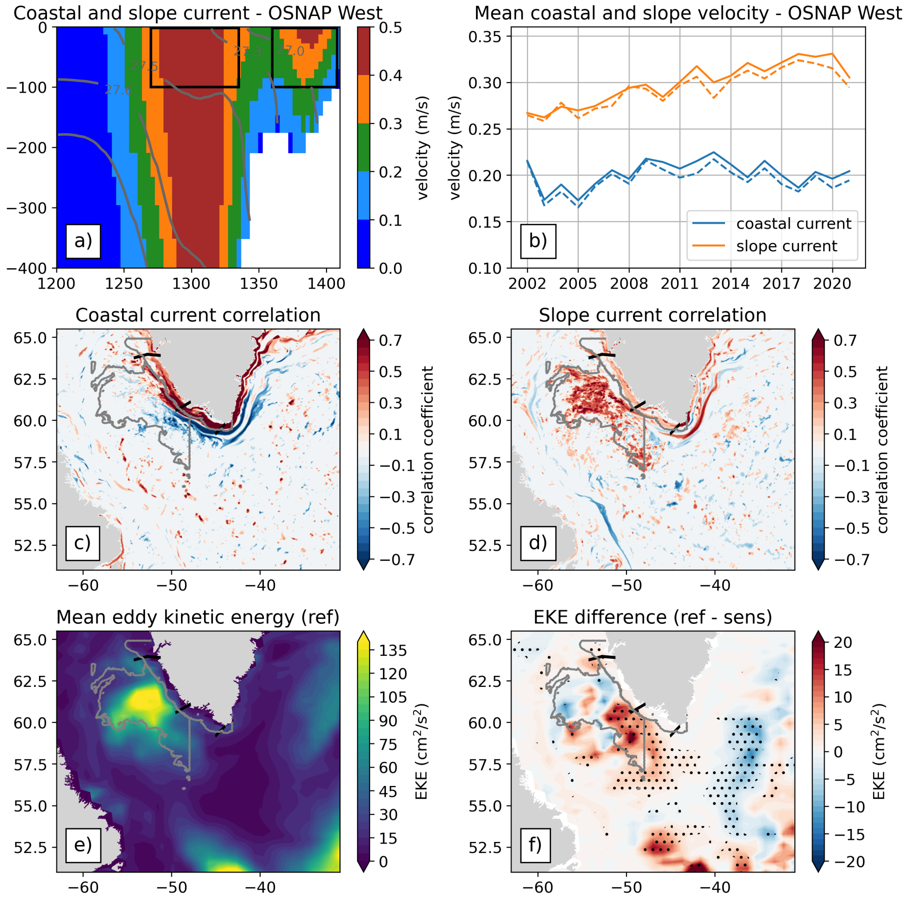

Figure 3. (a) Mean (2002–2021) current velocity magnitude at OSNAP West. Black boxes show the coastal and slope current cores. (b) Annual mean coastal (blue) and slope current (orange) velocity time series. Dashed/solid is the SENS/REF. (c) Cumulative correlation between the surface horizontal density gradient and WGCC at OSNAP West, CD, and Fylla Bank (south to north cross sections in black lines). (d) Cumulative correlation at the slope current. (e) The mean EKE at 100m depth from the REF. (f) Mean EKE difference (REF minus SENS). Stippling indicates the significant areas.

In both experiments, the majority of eddies are formed in the northeast corner of the LAB, just off of CD, marked in Figure 1a), from large topographic changes which generate Irminger Rings (Bracco et al., 2008), shown by the patch of high EKE (Figure 3e). As the eddy field is highly variable, we coarsen the EKE field to $\approx 1/4°$ for smoothing. When computing the mean EKE difference between the REF and SENS (Figure 3f), we find significant positive EKE differences just southwest of OSNAP West where lower salinities leak into the interior (Figure 2a). The positive difference does not extend over the whole eddy shedding region, particularly where the EKE is greatest just north of CD. Gou et al. (2021) observed that the WGCC splits into multiple branches at Juliannehaab Bight but merges again at CD. Boundary current eddies are induced from baroclinic instabilities as the WGC meanders (Pacini & Pickart, 2022), which may explain the positive EKE difference where the local density gradient between the fresh (and cool) boundary current and saltier interior from increased runoff. This likely causes baroclinic instabilities to form or strengthen resulting in more eddies. However, such eddies are typically smaller and shallower than eddies shed at CD from local topography (Pacini & Pickart, 2022). This could explain for differences in EKE between REF and SENS to not be significant (stippling in Figure 3f). Another reason is the large internal variability of mesoscale dynamics in this region in both simulations.

Enhanced EKE southwest of Greenland in REF indicates a role for eddies in the near-surface freshening (and cooling) in this region being all triggered by increased Greenland FWFs and having implications for preconditioning of and restratification after deep convection (Gelderloos et al., 2011; Chanut et al., 2008).

3.3 Eastward deepening of mixed layer depth

We investigate the changes in MLD between the experiments to identify a potential impact by enhanced Greenland FWFs over the recent two decades. Deep convection typically occurs yearly in the LAB but differs in strength (Yashayaev & Clarke, 2008; Zunino et al., 2020). There have been periods of deep convective activity occurring in the IRM, particularly in 2009, 2012, and 2015–2018 from favorable preconditioning the preceding years (Zunino et al., 2020; de Jong & de Steur, 2016; Piron et al., 2016; Yashayaev & Loder, 2017; Piron et al., 2017; Rühs et al., 2021). Labrador Sea Water (LSW) is formed at mid-depth (500–2000m) during convection and can spread eastward into the IRM on time scales of 1–3 years (Lavender et al., 2000; Straneo et al., 2003; Yashayaev et al., 2007; Chafik et al., 2022; Böning et al., 2023). Rühs et al. (2021) speculated that freshening trends in the SPNA may have resulted in this intensified deep convection in the IRM from 2015–2018. While it is observed that changes in MLD are dominated by winter air-sea heat fluxes versus changes in stratification (de Jong et al., 2012; de Jong & de Steur, 2016; Piron et al., 2017), the question remains whether traces of Greenland melt may have partially contributed to the deepening of mixed layers in the east. Note, the atmospheric forcing is the same for REF and SENS and hence surface fluxes are virtually equal thus allowing attribution of MLD differences between REF and SENS to the enhanced Greenland runoff.

We focus on the years 2009–2013, just prior to the period of strong deep convection, and 2015–2018. The long term mean (2002–2021) shows deepest MLDs primarily in the central LAB (Figure 4a). In 2009–2013 deep convection was confined to the LAB (pink contour in 4a, b), while 2009 and 2012 were individual years where the MLDs reached depths greater than 1500m in the LAB and ≈1000m south of Cape Farewell (MID, cf. Figure 1a) (Figure S4a, b).

Deep convection occurred in both the LAB and IRM (black contour in Figure 4a, b) in 2015–2018. When computing the maximum MLD difference (REF minus SENS) from 2015–2018, we find significantly deeper MLDs in the IRM in REF than in SENS, with differences ranging from 200–600 m (Figure 4b). This is seen in the convective resistance (CR), defined by the amount of vertical integral buoyancy anomaly that must be removed in order to overcome stratification and mix down to a particular depth (h=1500m) (Gillard et al., 2022; Frajka-Williams et al., 2014; Holdsworth & Myers, 2015) (Supporting Information S5). Shallower MLDs dominate the LAB in REF, particularly between WEST and MID (Figure 4b), coinciding with significant, higher CRs in REF in the LAB (Figure S5b).

To investigate whether Greenland melting has contributed to an eastward deepening of MLDs in 2015–2018, we look at winter mean depth profiles averaged along the pDCA over maximum band of ±5° latitude from 2009–2013. Stratification increases up to 20% in REF with respect to SENS in the LAB (WEST) below 300 m (Figure 4c).

Stratification difference between REF and SENS in the IRM (EAST) shows a prominent dipole with reduced stratification in REF up to 30% above 1000–1500 m and greater stratification below. There is an outstanding reduction in passive meltwater tracer concentration in EAST in REF compared to SENS below the same depth interface contoured by said stratification response dipole (red patch in Figure 4d), i.e. aligned with the stronger stratification in REF. Tracer content is enhanced above this 1000–1500 m interface matching the weaker stratification. For WEST and MID, the cross-section shows enhanced tracer content over the entire column which is expected since FWFs in REF are larger than in SENS. Together, these patterns hint at freshwater being convected to greater depth in the LAB in SENS prior to being exported to EAST with the LSW (deeper LAB MLDs in SENS in Figure 4c, d). Since we are averaging over 5 years, there is a smoothing over the annual maximum MLDs, where the MLD discrepancy between REF and SENS is strongest in 2009 and 2012 (Figure S4a, c).

We interpret these signals such that firstly, enhanced Greenland FWFs cause reduced deep mixing in the LAB, leading to meltwater being entrained at a shallower depth before being exported to the IRM. Secondly, the meltwater now residing between 200–1000 m (instead of further down) acts to decrease stratification between mid-depth and the surface, also illustrated by a reduced CR in EAST in REF versus SENS (Figure S5c, green line). As a result, the water column in the central to eastern IRM was preconditioned for deeper mixing prior to the occurrence of favorable atmospheric conditions triggering convection in 2015 and following years. A shift in deep convection center from the LAB to the IRM under enhanced freshwater input from Greenland appears to be a common response among coupled climate models (e.g., Devilliers et al., 2021; Martin et al., 2022; Martin & Biastoch, 2023).

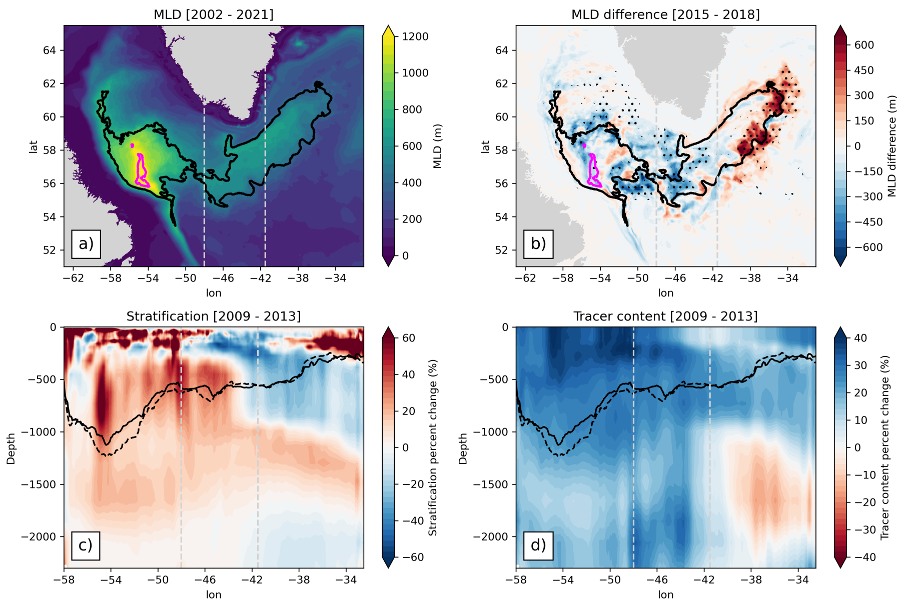

Figure 4. (a) The maximum 2002–2021 mean MLD (REF). (b) The MLD difference (REF minus SENS) in 2015–2018. Stippling indicates significant areas, the pink/black contour shows the deep convection area in 2009–2013/2015–2018. (c) The winter mean (2008–2013) stratification percent change of REF compared to SENS averaged over the pDCA. (d) The Greenland tracer content percent change. Black solid/dashed line indicates the mean maximum MLD of the REF/SENS. The gray dashed, vertical lines indicate the WEST/MID/EAST separations.

Thus, we suggest that preconditioning of the IRM at mid-depth began in 2009–2013 when the LAB's MLDs exceeded $z_{critical}$ allowing for deep entrainment of meltwater. This process preceded the propagation of fresher waters into the IRM in 2017–2018 (Biló et al., 2022) originating from the Eastern North Atlantic salinity anomaly of 2012–2016 (Holliday et al., 2020). It is noteworthy that the comparatively small but realistic increase in FWFs in REF helped reduce CR to as low as 0.2 m^2/s^2 in EAST, which was not the case for EAST since the GSA in the late 1980s, e.g. the minimum CR in WEST was twice as strong in recent years as during the 1990s (Figure S5c). We highlight that: 1) enhanced runoff of Greenland meltwater is not vertically mixed as deep from greater/reduced CRs/MLDs in the LAB, 2) stratification in the IRM decreases upon more freshwater entering the upper 1000 m enabling deeper MLDs there, and 3) increasing Greenland FWFs reduces the IRM's CR after 2009 reaching even lower levels than the LAB.

4 Conclusions

In this study we analyze two 1/20° ocean/sea-ice model simulations with the same surface forcing except for Greenland freshwater input: REF containing realistically varying FWFs, and SENS with reduced FWFs based on a climatological mean (1961–2000). We conclude that while there has not yet been a significant impact by accelerated Greenland melting on large scale circulation, the most notable emerging imprints are:

1) The boundary current shows the largest signal in hydrographic changes. There is a significant freshening around the WGC system which intrudes into the eddy shedding region, reducing the density on and near the shelf. Cooler temperatures dominate the boundary currents, with enhanced sea ice coverage in the northwest perimeter of the Labrador basin.

2) The shelf's reduced density increases the density gradient between the slope current and interior Labrador/Irminger seas, where the coastal and slope currents strengthen i.e. at OSNAP West. The increase in density gradients and current strength can result in barotropic and baroclinic instabilities leading to intensified eddy shedding. The increased eddy activity southwest of Greenland favors an enhanced "leaking" of meltwater into the Labrador Sea.

3) The intrusion of relatively fresher waters into the deep convection region reduces—but does not prohibit—deep mixing in the Labrador Sea. The signal is entrained to shallower depths only and is exported into the Irminger Sea via LSW, reducing stratification between the surface and mid-depth. We argue that our experiment demonstrates that by this process, enhanced Greenland runoff has contributed to a lowering of convective resistance in the Irminger Sea and an eastward shift of deep convection in 2015–2018.

Data Availability Statement

All (processed) model data and scripts needed for Figures 1–4 are made available using the GEOMAR data management platform under the identifier: `hdl.handle.net/20.500.12085/e3cd8f8c-07bd-4955-b77a-504377e299ac` (Schiller-Weiss et al., 2024).

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