AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070969

Key Points:

- Rapid offshore exchange of freshwater from the West Greenland Current accumulates in the interior convective part of the Labrador Sea
- A lagged freshwater signal from the Greenland ice sheet enters the Labrador Sea from the south
- Narrow boundary currents are important for freshwater transport and distribution, requiring simulations with eddy-resolving resolution

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2

Correspondence to:
L. C. Gillard,
gillard2@ualberta.ca

Citation:
Gillard, L. C., X. Hu, P. G. Myers, and J. L. Bamber (2016), Meltwater pathways from marine terminating glaciers of the Greenland ice sheet, *Geophys. Res. Lett.*, *43*, 10,873–10,882, doi:10.1002/2016GL070969.

Received 24 AUG 2016
Accepted 25 SEP 2016
Accepted article online 29 SEP 2016
Published online 25 OCT 2016

Meltwater pathways from marine terminating glaciers of the Greenland ice sheet

Laura C. Gillard[1], **Xianmin Hu**[1], **Paul G. Myers**[1], **and Jonathan L. Bamber**[2]

[1] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada, [2] School of Geographical Sciences, University of Bristol, Bristol, UK

Abstract The Greenland ice sheet (GrIS) stores the largest amount of freshwater in the Northern Hemisphere and has been recently losing mass at an increasing rate. An eddy-permitting ocean general circulation model is forced with realistic estimates of freshwater flux from the GrIS. Two approaches are used to track the meltwater and its trajectory in the ocean. We show that freshwater from western and eastern GrIS have markedly different fates, on a decadal time scale. Freshwater from west Greenland predominantly accumulates in Baffin Bay before being exported south down the Labrador shelf. Meanwhile, GrIS freshwater entering the interior of the Labrador Sea, where deep convection occurs, comes predominantly (~80%) from east Greenland. Therefore, hosing experiments, which generally assume a uniform freshwater flux spatially, will not capture the true hydrographic response and regional impacts. In addition, narrow boundary currents are important for freshwater transport and distribution, requiring simulations with eddy-resolving resolution.

1. Introduction

The Greenland ice sheet (GrIS) is the second largest ice sheet in the world. The GrIS has lost large amounts of mass recently [*Sasgen et al.*, 2012; *Shepherd et al.*, 2012]. Since the early 1990s, the ice sheet has gone from close to balance to an imbalance exceeding 370 Gt/yr for 2009–2012 [*Enderlin et al.*, 2014], equivalent to 12 mSv. The GrIS has the potential to increase global sea level by 7.3 m [*Bamber et al.*, 2013] and could pass a threshold for the viability of the ice sheet for a temperature increase above preindustrial of 3.1°C [*Robinson et al.*, 2012]. The enhanced mass loss from the GrIS comes from a combination of factors including the following: increasing surface air temperatures [*Box et al.*, 2009; *Hanna et al.*, 2013], a positive feedback between increases in Arctic temperatures and decreasing Arctic sea ice [*Hanna et al.*, 2013], and increasing presence of relatively warm ocean temperatures contacting the GrIS [*Holland et al.*, 2008; *Myers and Ribergaard*, 2013; *Straneo and Heimbach*, 2013; *Jackson et al.*, 2014]. The largest increases in freshwater flux from the GrIS have occurred in the southeast and southwest sectors, close to areas of dense water formation in the North Atlantic Ocean.

The southern part of the North Atlantic Subpolar Gyre (SPG) flows across the North Atlantic as the North Atlantic Current (NAC) and continues as the Irminger Current, circulating along Reykjanes Ridge [*Fratantoni and Pickart*, 2007] (Figure 1). The warmest water that arrives near the Greenland shelf break has a significant seasonal cycle, at around a depth of 300 m, dependent on the advection time from the Irminger Basin, which may accelerate further melt from the GrIS [*Grist et al.*, 2014]. The Irminger Current flows along the southeast coast of Greenland where it merges with two relatively fresh currents, made up of Arctic and Greenland melt waters [*Bacon et al.*, 2014]. This merged current mixes and is modified as it rounds Cape Farewell and subducts under the low-salinity polar water, forming the West Greenland Current (WGC) [*Straneo*, 2006; *Fratantoni and Pickart*, 2007; *Melling et al.*, 2008; *Myers et al.*, 2009]. The WGC continues northward through Davis Strait into Baffin Bay, with less saline, cold waters at the surface and relatively warm, saline water at intermediate depth [*Myers et al.*, 2009; *Curry et al.*, 2014].

Additionally, relatively warm Atlantic waters flow from the NAC through the Greenland-Scotland Ridge into the Nordic Sea. The Atlantic waters enter the Arctic Ocean through Fram Strait as the West Spitsbergen Current or through the Barents Sea. The recirculated modified Atlantic and Arctic waters enter the North Atlantic Ocean through Fram Strait, with the East Greenland Current (EGC).

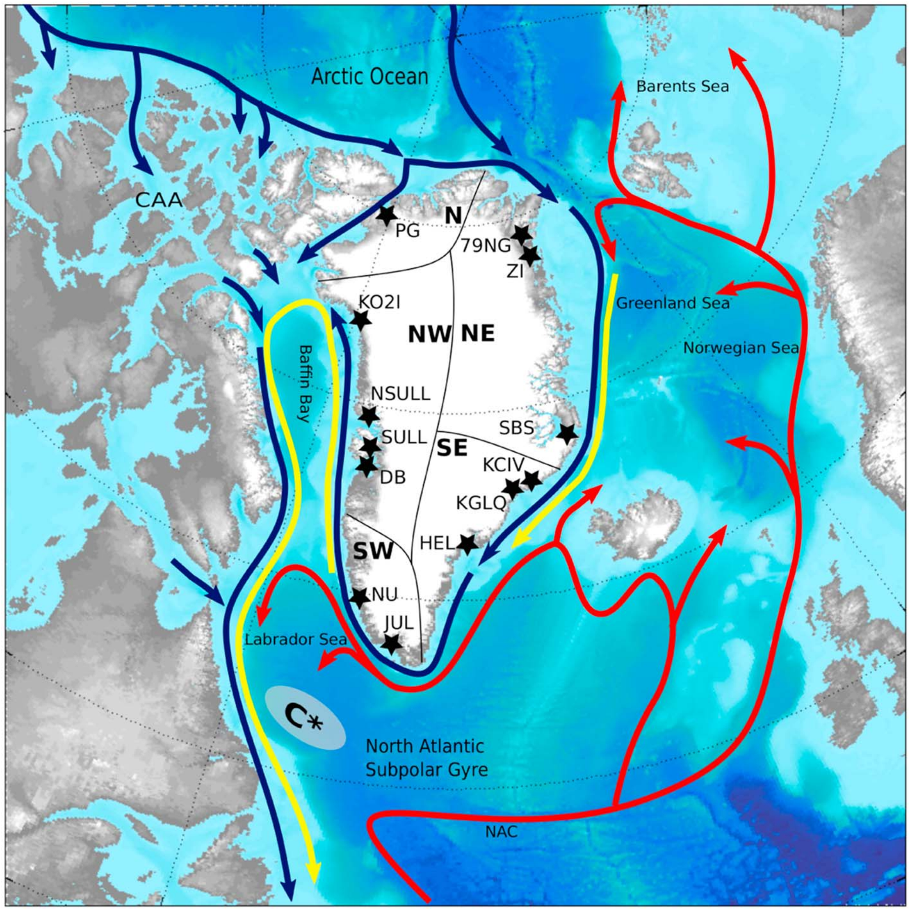


Figure 1. Ocean Circulation around Greenland and 13 outlet regions along the Greenland ice sheet. Relatively warm Atlantic waters are seen in red, and the yellow lines represent the mixed and cooled Atlantic waters. Arctic water and freshwater pathways are shown in blue lines. The Labrador Sea deep convection site is approximately located at the C*. The black stars show the distribution of the 13 outlet regions examined along the coast of the Greenland ice sheet and the sectors they are found in, north (N), northwest (NW), southwest (SW), southeast (SE), and northeast (NE). For exact locations, see Table S1.

The Labrador Sea (the western part of the North Atlantic SPG) has significant biological activity, icebergs, sea ice, and intense air-sea interactions with extreme winds and cold temperatures [*Marshall et al.*, 1998]. Buoyancy-driven convection in the central Labrador Sea may be sensitive to freshwater input, lowering the density of the surface waters, reducing convection [*Aagaard and Carmack*, 1989; *Straneo*, 2006; *Myers et al.*, 2009; *Weijer et al.*, 2012]. Sources of high-latitude freshwater include as follows: river runoff, waters from the Arctic Ocean through the Canadian Arctic Archipelago (CAA) and Hudson Strait, sea ice, icebergs, and the GrIS [*Dickson et al.*, 2007]. All these sources have increased, with much of this increase focused on the Labrador Sea [*Yang et al.*, 2016]. Additionally, freshwater input into Baffin Bay may impact the dynamic height gradient between the Arctic Ocean and Baffin Bay [*Marsh et al.*, 2010; *Castro de la Guardia et al.*, 2015], modifying the inflow of Arctic Waters through the CAA into Baffin Bay.

The convection in the Labrador Sea links surface waters to the formation of the North Atlantic Deep Water [*Weijer et al.*, 2012], feeding the Atlantic Meridional Overturning Circulation (AMOC) [*Dickson et al.*, 2007; *Weijer et al.*, 2012]. The sensitivity of the AMOC to freshwater input varies depending on different climate model simulations, though they come to the same result, with increased freshwater flux from the GrIS the AMOC will undergo a weakening phase [*Fichefet et al.*, 2003; *Swingedouw et al.*, 2014]. However, due to the coarse resolution of climate models, the formation of buoyant boundary currents tight to the coast of the Labrador Sea can be unresolved. Thus, we look at the pathways of the low-salinity melt waters from these coastal glaciers and where it is taken up in the surrounding basins. *Luo et al.* [2016] show using a high-resolution numerical model that at least half of the meltwater originating from southeast Greenland in a given summer is transported west into the northern Labrador Sea, while less than 15% of the surface meltwater from southwest Greenland goes westward.

Here we will examine the eventual fate of the Greenland meltwater as it is taken up within the subpolar gyre and Baffin Bay over longer time scales. By considering all regions of the GrIS and not just the southern coasts, we show for the first time a spatial breakdown of the Greenland meltwater that enters the convective interior of the Labrador Sea, by several routes and with multiple time scales.

2. Methods

To examine the fate of a specific water mass, we used a well-tested [*Lique et al.*, 2010; *de Boisséson et al.*, 2012; *Hu and Myers*, 2013] offline Lagrangian tool, ARIANE [*Blanke and Raynaud*, 1997; *Blanke et al.*, 1999]. Although ARIANE provides only the advection scheme, with the diffusion and mixing process partly handled by the source (e.g., numerical model's velocity fields), it still can provide useful information on the large-scale ocean circulation.

To compute three-dimensional (3-D) trajectories, ARIANE is provided with ocean velocity fields. In this study we take the velocity fields from two different numerical simulations. Both simulations are regional configurations of a coupled ocean-sea ice model based on the Nucleus for European Modelling of the Ocean (NEMO) version 3.4 [*Madec*, 2008]. We use the Arctic Northern Hemisphere Atlantic (ANHA) configuration for the ANHA4 and ANHA12 simulations. This configuration covers the whole Arctic Ocean and North Atlantic and part of South Atlantic, with two open boundaries: one at Bering Strait and the other at 20°S. The configuration's mesh grid is extracted from a global tripolar grid, ORCA [*DRAKKAR et al.*, 2007]. ANHA4 has a 1/4° horizontal grid with resolution ranging from ∼5.79 km in Northern Canada to ∼27.9 km at the equator. ANHA12 has a 1/12° horizontal resolution, with a resolution of ∼1.93 km near the artificial pole over Northern Canada and ∼9.3 km at the equator. Both configurations have 50 vertical model levels. The configuration is coupled with the Louvain la-Nueve Ice Model (LIM2) sea ice thermodynamic and dynamic numerical model [*Fichefet and Maqueda*, 1997] with initial and monthly open boundary conditions provided by Global Ocean Reanalyses and Simulations (GLORYS) [*Ferry et al.*, 2008]. The atmospheric forcing data, provided by Canadian Meteorological Centre's global deterministic prediction system reforcasts (CGRF) data set [*Smith et al.*, 2014], have hourly 33 km resolution for the following fields: 10 m surface wind, 2 m air temperature and humidity, downward shortwave and longwave radiation, and total precipitation.

The ANHA4 simulation uses interannual monthly runoff from *Dai et al.* [2009] except for the Greenland region which is provided by *Bamber et al.* [2012]. The ANHA12 simulation uses monthly climatology runoff [*Dai et al.*, 2009]. The detailed settings of each simulation are also discussed in previous studies using this configuration [*Holdsworth and Myers*, 2015; *Dukhovskoy et al.*, 2016].

The analysis was done using the output (5 day average) velocity fields for years 2002–2010 for ANHA4 and ANHA12 for each of the five sectors (shown in Figure 1 and listed in Table S1 in the supporting information) to examine the pathways of GrIS melt found near the mouth of marine terminating glaciers. Virtual particles (hereafter, called particles) were released at the latitudes and longitudes (associated with the corresponding sectors of Greenland as shown in Figure 1 and defined in Table S1). The locations were close to the model coastline, outside the mouth of the marine terminating glacier fjords. To capture the estuarine circulation of a fjord and mixing with interior ocean waters, it requires an extremely high resolution, which is beyond the ability of our current simulations.

To simulate how the surface water outside each outlet region's fjord get taken up by the surrounding ocean currents, particle initial positions (∼1000) were homogeneously distributed in space in the first 21 model grid levels of the water column (77.85 m) and then were integrated forward in time for 5 years. This was repeated for each successive starting year, with the final probabilities determined by taking the particle positions over all years. To present the pathways of the water in a more meaningful (statistic) way, we defined five likelihood categories (Very High, High, Medium, Low, and Very Low), based on the probability of the occurrence of all particles in any given grid box during the entire 5 year period (Table S2). The depth terminology used throughout this manuscript is defined in Table S2. Additional information regarding the methodology can be found in a previous dissertation [*Gillard*, 2015].

3. ARIANE Results

We first use a Lagrangian virtual float tool to examine the pathways of the freshwater melt from five sectors of the GrIS (Figure 1). One representative glacier is chosen for each region. Results for additional glaciers in each region are given in the supporting information.

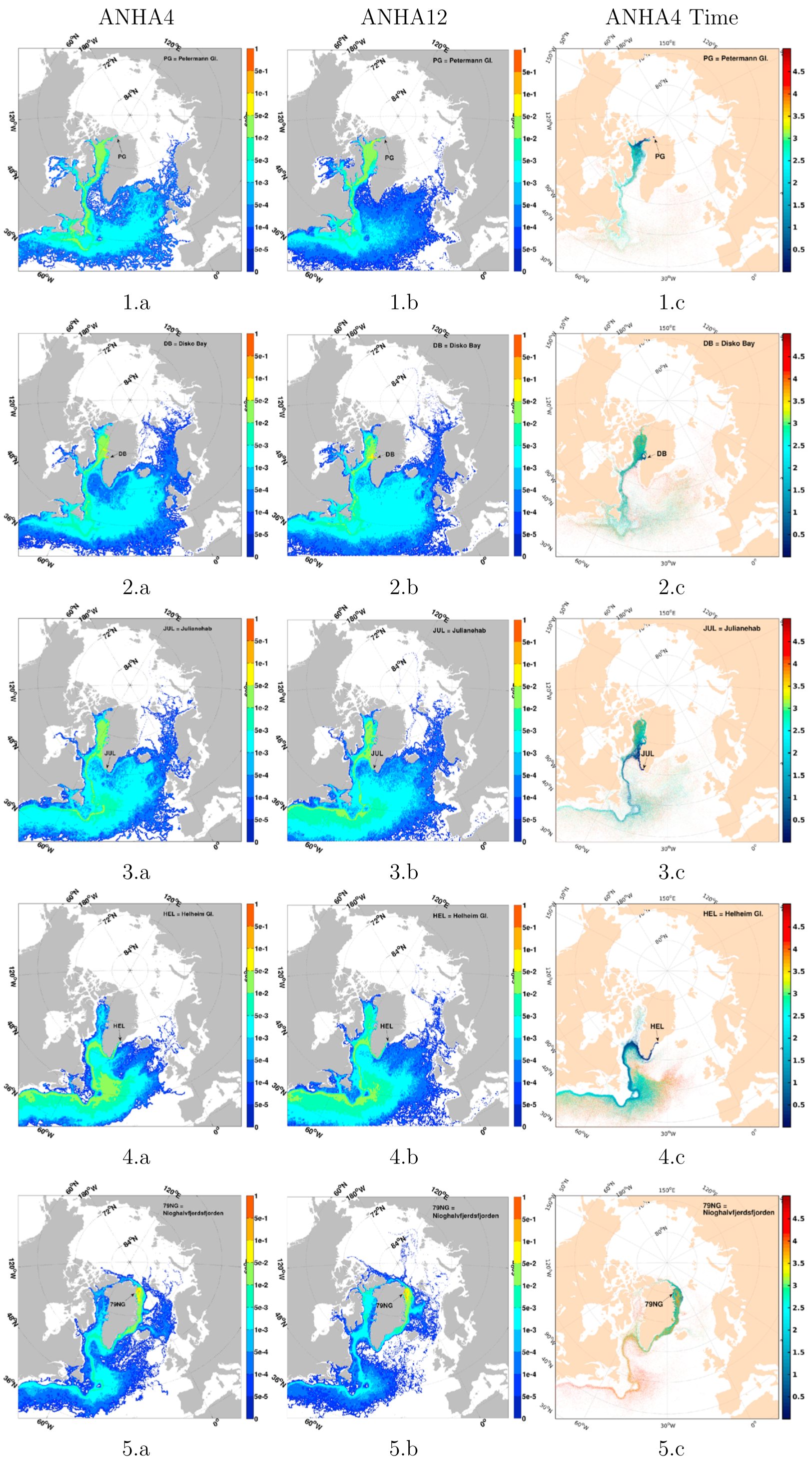
Surface freshwater by the outlet region of Petermann Glacier (PG) (Figure 2.1) has a high probability to head south through Nares Strait at surface and subsurface depths and cascades (due to topographic influence in Kane Basin) deeper into the water column and enters Baffin Bay interior at subintermediate depths. These waters do not significantly extend to the West Greenland shelf. They do recirculate at surface and subsurface depths and then enter central Baffin Bay after flowing south in the Baffin Island Current with some of these waters remaining even after 5 years. Most of the water does travel south through Davis Strait, leaving after 2 to 3 years. Significant inflow and recirculation in Hudson Strait is seen, consistent with previous studies [*Straneo and Saucier*, 2008].

Most of the freshwater is then carried south by the Labrador Current. The very low probabilities next to the coast (in this and subsequent figures) suggest very little glacial water gets into the inshore branch of the Labrador Current, which is instead fed by outflow from Hudson Bay [*Loder et al.*, 1998]. Much of the freshwater rounds the tip of the Grand Banks, to reach the Scotian shelf within 5 years. There is offshore exchange south of Flemish Cap into the NAC (consistent with observations [*Fratantoni and McCartney*, 2010]), albeit with much higher probabilities in the coarser resolution run. There are very low probabilities offshore of the Labrador Current suggesting little exchange into the interior of the Labrador Sea in this area.

Here we will discuss Disko Bay (Figure 2.2) and Julianehab (JUL) (Figure 2.3), as results for other glaciers in the northwest sector (Figure 1), i.e., the Baffin Bay glaciers, behave similarly (Figures S1.2–S1.4). The freshwater influx from these glaciers behaves similar to that from PG in Baffin Bay, so we will not repeat that discussion from above, except where the results are different. Since JUL discharges directly onto the West Greenland shelf, we do see high probabilities there. The main difference is that for the particles released near the Baffin Bay glaciers, they have a much greater probability of being transported offshore into the SPG. Even if the probabilities are higher in ANHA4, we still do not see significant offshore exchange in ANHA12. These particles are then quickly mixed through the SPG and reach the interior of the Newfoundland Basin with medium probabilities. Some particles circulate around the SPG within 5 years, and there is a pathway into the southern interior of the Labrador Sea from the south.

We discuss results from Helheim Glacier (HEL) (Figure 2.4), which has similar behavior to all the southeast outlet regions as well as several from north of Denmark Strait, including Kangerdlugssuaq (KGLQ), Kong Christian IV (KCIV), and Scoresby Sund (SBS) (Figures S1.5–S1.7). There is a tongue of high probability in the EGC/WGC, as the particles (and freshwater) are swept away within 1 year by the boundary current. There is also a recirculation of EGC waters south of Cape Farewell, as observed by *Holliday et al.* [2007, 2009]. There is significant transport into Baffin Bay by the WGC. In all cases, particles circulate around the northern Labrador Sea into the Labrador Current. Since they are offshore of the Baffin Island Current, there is only a low probability of penetration into Hudson Strait. Once in the Labrador Current, there is significant offshore exchange into the NAC and the Labrador Sea at deep depths. Particles are seen offshore in the region of the Northwest Corner within 3 years of release and reach the convective interior of the Labrador Sea from the south within 5 years. Additionally, the particles released from the east Greenland glaciers show offshore exchange into the Labrador Sea from the WGC (as identified by *Myers et al.* [2009] and *Rykova et al.* [2015]), occurring within the first year.

Surface waters found by the northeast outlet regions of Nioghalvfjerdsfjorden (79NG) (Figure 2.5) (similarly Zachariae Isstrom (ZI), Figure S1.8), have a very high probability of recirculating close to the outlet region at surface to subsurface depths. Some of the particles are transported into the Arctic Ocean, where they flow west north of Greenland and enter Nares Strait. However, the majority flow south with the EGC, although this process takes around 3 years. There is significant offshore exchange south of the Greenland Sea around the Jan Mayen Fracture Zone in the Jan Mayen Current [*Mauritzen et al.*, 2011]. The particles continue south through Denmark Strait and around Greenland, following the EGC, WGC, and the Labrador Current. Penetration into Baffin Bay occurs but at lower probability compared to the glaciers farther south. Most particles continue south in the Labrador Current, 4 to 5 years after release, with little exchange offshore north of the Grand Banks (especially in ANHA12).



1.a 1.b 1.c

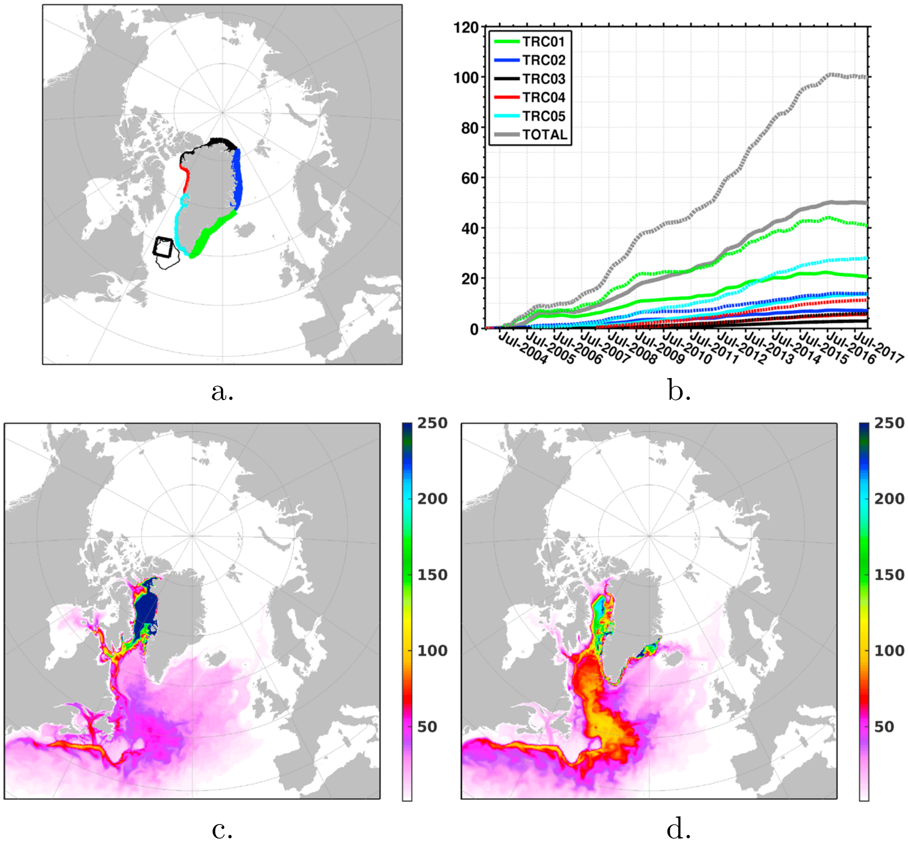
2.a 2.b 2.c

3.a 3.b 3.c

4.a 4.b 4.c

5.a 5.b 5.c

Figure 2. Forward transport of ARIANE virtual particles at selected outlet regions. Every row shares a similar outlet region, noted by the arrow in the figure with the full name on the top right-hand side of the figure. Each column separates the outlet region by the two experiments (ANHA4 and ANHA12, respectively) and a time evolution analysis in years of ANHA4. This figure contains one outlet region for the five separate sections along Greenland. The first two columns show the probability, a given virtual particle to be found in a given model grid cell, based on 5 year averages from the ARIANE Lagrangian model run in forward mode. Particle initial positions (~1000 per insertion (yearly) are homogeneously distributed in space in the first 21 model grid levels of the water column (77.85 m). Values here correspond to the percentage out of all particles and grid cells that particles can be found in a given grid cell. The third column shows the time evolution in years of the virtual particles from the ANHA4 experiment. For an analysis on the other eight outlet regions, see Figure S1.



a.

b.

c.

d.

Figure 3. Five passive tracers for different regions along the coast of Greenland using the ANHA4 configuration. Passive tracers are released from 1 January 2004, proportional to the amount of runoff from Greenland at each time step and each grid cell. (a) The location of five passive tracers, corresponding to the location of freshwater input. The thick black box shows the location of the central Labrador Sea, and the thin black polygon outlines the 3000 m deep central basin. (b) The evolution of central Labrador Sea tracer storage (solid line for the central Labrador Sea and dash line for the deep basin in Figure 3a) integrated over the region with units of volume (km^3). (c) Vertical integral concentration (units of kg/m^2) of the passive tracer released from southwest Greenland (TRC05, color in cyan in Figures 3a and 3b) by the end of 2010. (d) Vertical integration concentration (units of kg/m^2) of the passive tracer released from southeast Greenland in 2004 (TRC01, green color in Figures 3a and 3b) by the end of 2010.

4. Discussion

Given the potential significance of the divergent pathways for west and east Greenland particles (and thus freshwater), we wonder about the sensitivity of the results to the use of ARIANE. We thus repeat an experiment [*Dukhovskoy et al.*, 2016] with ANHA4, except defining five passive tracers for the different regions of coastal Greenland (Figure 3a). As discussed in greater detail in that paper [*Dukhovskoy et al.*, 2016], passive tracers are released from 1 January 2004, proportional to the amount of runoff from Greenland at each time step and each grid cell.

Integrated concentrations of the passive tracer after 7 years (the end of 2010) are shown for the southwest (Figure 3c) and southeast (Figure 3d) tracer release locations. In general, the tracer field is consistent with ARIANE. The tracer released from southwest Greenland (Figure 3c) accumulates mainly in Baffin Bay and then flows south along the Labrador Current to the Scotian Shelf. Most of the offshore exchange is still around Flemish Cap and the Grand Banks. There is limited take-up of this tracer in the interior of the Labrador Sea, with entry coming from the south. Some of the southeast Greenland tracer penetrates Baffin Bay (Figure 3d). However, very little of the tracer is seen on the Labrador and Scotian shelves. Instead, there is significant accumulation offshore in the Labrador Sea and the Newfoundland Basin. Plumes of higher tracer concentration recirculating back into the Irminger Sea are seen south of Cape Farewell, consistent with the circulation pattern of *Holliday et al.* [2007, 2009].

To quantify the take-up of the regional Greenland passive tracers in the interior of the Labrador Sea (given in Figure 3a), we look at two definitions of the interior of the Labrador Sea. One is the same small interior box used in a previous study [*Dukhovskoy et al.*, 2016], while the other is based on the 3000 m isobath and includes the region where deep convection occurs (given in Figure 1). This confirms the picture from ARIANE and the passive tracer concentration maps. As seen in Figure 3d, tracer from southeast Greenland is rapidly transported into the Labrador Sea soon after it is turned on, with continual and significant accumulation during the entire run. After 7 years, there is approximately 3 times as much of the tracer from southeast Greenland in the Labrador Sea interior as from southwest Greenland. In fact, there is as much of the tracer from the more northerly glaciers of the Nordic Seas part of east Greenland as from southwest Greenland.

Recycling our forcing over 2004–2010 to provide an extra 7 years of simulation, as in *Dukhovskoy et al.* [2016], it is evident from Figure 3b that the TRC05 has a lagged signal of accumulation into Labrador Sea, showing that meltwater from southwest Greenland will eventually be taken into the Labrador Sea, after circulating the basin, and being taken offshore around the Grand Banks.

In this study, we trace the pathways of meltwater from Greenland into the basin interiors. Since we cannot represent the fjord dynamics and the mixing that occurs within them, we release the particles in the upper (low salinity) water column on the shelf, after departing the fjord. The response of the ocean to the added freshwater from Greenland is an important question and has been looked at in many studies [*Aagaard and Carmack*, 1989; *Fichefet et al.*, 2003; *Straneo*, 2006; *Dickson et al.*, 2007; *Myers et al.*, 2009; *Marsh et al.*, 2010; *Weijer et al.*, 2012; *Straneo and Heimbach*, 2013; *Swingedouw et al.*, 2014; *Castro de la Guardia et al.*, 2015]. However, most such studies have been focused on changes in sea level [*Fichefet et al.*, 2003; *Marsh et al.*, 2010; *Rignot and Mouginot*, 2012; *Castro de la Guardia et al.*, 2015], deep water formation [*Straneo*, 2006; *Weijer et al.*, 2012; *Swingedouw et al.*, 2014], the AMOC [*Fichefet et al.*, 2003; *Dickson et al.*, 2007; *Weijer et al.*, 2012; *Swingedouw et al.*, 2014], and the large-scale climate response [*Fichefet et al.*, 2003; *Straneo and Heimbach*, 2013] rather than a detailed examination of the pathways. A study [*Dukhovskoy et al.*, 2016] examined pathways of melt from Greenland using passive tracers, looking at its detailed take-up in basins such as the Labrador Sea and the Nordic Seas. However, they [*Dukhovskoy et al.*, 2016] do not break down the discharge by region, which we believe is important as the response is not homogeneous.

Almost all of the freshwater released from west and southwest Greenland is initially swept away by the boundary currents and ends up in Baffin Bay. For those glaciers in Baffin Bay, this is not surprising. Although there is significant exchange from the WGC into the interior of the Labrador Sea [*Myers et al.*, 2009; *Rykova et al.*, 2015], the freshwater released from the glaciers in southwest Greenland feeds the inshore shelf component of the WGC and is thus rapidly transported north to Baffin Bay (Figure S2). This is consistent with a more idealized modeling study [*Castro de la Guardia et al.*, 2015] and supports their contention that circulation within Baffin Bay and the exchange through the CAA are very dependent on the melt from West Greenland.

From Baffin Bay, most of the particles that leave flow south in the Baffin Island Current and the Labrador Current. There is some inflow into Hudson Strait [*Straneo and Saucier*, 2008]. Note that almost no particles get into the inshore component of the Labrador Current, which is instead fed by freshwater from the Hudson Bay System. There is little direct exchange from the Labrador Current into the Labrador Sea, and thus, this freshwater is unlikely to have a direct short-term impact on convection, unlike that observed in water hosing experiments [*Fichefet et al.*, 2003; *Myers*, 2005; *Swingedouw et al.*, 2006]. Many of the particles actually continue south to the Scotian shelf and the mid-Atlantic Bight, a region known to be impacted by SPG waters [*Li et al.*, 2014]. Offshore exchange into the SPG is concentrated around Flemish Cap and the Grand Banks [*Fratantoni and McCartney*, 2010]. Given that this exchange path involves interaction with the NAC, significant dilution of the freshwater signal will occur, limiting the transport of low-salinity signals.

The particles and passive tracer from the glaciers of eastern Greenland (such as HEL, Figures 2.4 and 3d) more easily reach the interior of the Labrador Sea. This occurs both due to exchange from the WGC and also due to circulation around the Labrador Sea. The exchange from the WGC is rapid, occurring within 6 months of release (Figures 2 and S2). As the particles are farther offshore along a deeper isobath, they recirculate back to the north (Figure S2) in the Labrador Sea counter current [*Lavender et al.*, 2000]. These particles are then taken up into the Labrador Sea Water and transported to greater depths in winter.

It is widely accepted that freshwater fluxes from Greenland have been increasing since the mid-1990s [*Bamber et al.*, 2012], which will have an impact on the surrounding oceans [*Marsh et al.*, 2010]. However, this study clearly indicates that melt from different sectors of Greenland has markedly different pathways within the high-latitude seas. Melt and runoff from west and southwest Greenland will have a disproportionate effect on Baffin Bay and the Labrador Current. However, it is discharge from east Greenland that will impact the interior of the Labrador Sea, at least on decadal time scales, and thus potentially impact stratification, deep water formation, and the AMOC (and its associated heat transport). GrIS freshwater fluxes are also an important source of nutrients to coastal waters and affect, therefore, biological productivity [*Hawkings et al.*, 2016] as well as the hydrography. Our results indicate that the fate of freshwater and nutrient export from the GrIS is sensitive to the location that it enters the ocean and that narrow boundary currents play a critical role in the transport. Models that do not adequately resolve these boundary currents will struggle to capture this behavior. We note that roughly 50% of the total freshwater input is in the form of solid ice crossing the grounding line. A significant proportion of this is released as icebergs [*Bamber et al.*, 2012; *Marsh et al.*, 2015]. Currently, we do not include iceberg transport in our estimates of the fate of freshwater, which is the subject of ongoing research.

The inclusion of the entire coast of the GrIS in the analysis offers in detail, where and how the freshwater from all regions of the GrIS enters the Labrador Sea and Baffin Bay. A recent study [*Luo et al.*, 2016] also used passive tracers to examine the fate of meltwater from southwest and southeast Greenland. They found only limited amounts of runoff from southwest Greenland entering the northern Labrador Sea, while at least half of the runoff from southeast Greenland was found to enter that region. Work presented here agrees with previous results of *Luo et al.* [2016] and significantly extends the analysis.

For the first time it is shown that meltwater from different regions of Greenland penetrate into the interior of the Labrador Sea uniquely, on different time scales. We offer two routes for Greenland meltwater tracer entering and accumulating in the interior convective part of the Labrador Sea, a rapid offshore exchange from the WGC, as well a lagged, freshwater signal entering the Labrador Sea from the south. The different penetration of meltwater from different regions of Greenland into the convective interior of the Labrador Sea on different time scales is important for the formation of the Labrador Sea Water. This water mass is what makes the Labrador Sea important for the AMOC and its associated heat transport and large-scale climate response.

Acknowledgments
This work was funded by a Natural Sciences and Engineering Research Council of Canada (NSERC) grants awarded to P.G.M. (RGPIN 227438-09, RGPIN 04357, and RGPCC 433898). We would also like to thank G. Smith for the CGRF forcing fields and G. Garric for the GLORYS fields used to initialize the model. The model experiments were performed on Compute Canada infrastructure. The NEMO model is available through the NEMO website http://www.nemo-ocean.eu/. The ANHA configuration and its output can be accessed at http://knossos.eas.ualberta.ca/xianmin/anha/index.html. The author would like to thank the anonymous reviewers for their insightful comments and suggestions that have contributed to improving this paper.

References

Aagaard, K., and E. C. Carmack (1989), The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res.*, *94*(C10), 14,485–14,498, doi:10.1029/JC094iC10p14485.

Bacon, S., A. Marshall, N. P. Holliday, Y. Aksenov, and S. R. Dye (2014), Seasonal variability of the East Greenland Coastal Current, *J. Geophys. Res. Oceans*, *119*, 3967–3987, doi:10.1002/2013JC009279.

Bamber, J., M. Van Den Broeke, J. Ettema, J. Lenaerts, and E. Rignot (2012), Recent large increases in freshwater fluxes from Greenland into the North Atlantic, *Geophys. Res. Lett.*, *39*, L19501, doi:10.1029/2012GL052552.

Bamber, J. L., et al. (2013), A new bed elevation dataset for Greenland, *The Cryosphere*, *7*(2), 499–510, doi:10.5194/tc-7-499-2013.

Blanke, B., and S. Raynaud (1997), Kinematics of the Pacific equatorial undercurrent: An Eulerian and Lagrangian approach from GCM results, *J. Phys. Oceanogr.*, *27*(6), 1038–1053.

Blanke, B., M. Arhan, G. Madec, and S. Roche (1999), Warm water paths in the equatorial Atlantic as diagnosed with a general circulation model, *J. Phys. Oceanogr.*, *29*(11), 2753–2768.

Box, J. E., L. Yang, D. H. Bromwich, and L. Bai (2009), Greenland ice sheet surface air temperature variability: 1840–2007, *J. Clim.*, *22*(14), 4029–4049, doi:10.1175/2009JCLI2816.1.

Castro de la Guardia, L., X. Hu, and P. G. Myers (2015), Potential positive feedback between Greenland ice sheet melt and Baffin Bay heat content on the west Greenland shelf, *Geophys. Res. Lett.*, *42*, 4922–4930, doi:10.1002/2015GL064626.

Curry, B., C. Lee, B. Petrie, R. Moritz, and R. Kwok (2014), Multiyear volume, liquid freshwater, and sea ice transports through Davis Strait, 2004–2010, *J. Phys. Oceanogr.*, *44*, 1244–1266, doi:10.1175/JPO-D-13-0177.1.

Dai, A., T. Qian, K. E. Trenberth, and J. D. Milliman (2009), Changes in continental freshwater discharge from 1948 to 2004, *J. Clim.*, *22*(10), 2773–2792.

de Boisséson, E., V. Thierry, H. Mercier, G. Caniaux, and D. Desbruyéres (2012), Origin, formation and variability of the Subpolar Mode Water located over the Reykjanes Ridge, *J. Geophys. Res.*, *117*, C12005, doi:10.1029/2011JC007519.

Dickson, R., B. Rudels, S. Dye, M. Karcher, J. Meincke, and I. Yashayaev (2007), Current estimates of freshwater flux through Arctic and subarctic seas, *Prog. Oceanogr.*, *73*(3–4), 210–230.

DRAKKAR et al. (2007), Eddy-permitting ocean circulation hindcasts of past decades, *CLIVAR Exchanges*, *12*(3), 8–10.

Dukhovskoy, D. S., et al. (2016), Greenland freshwater pathways in the sub-Arctic Seas from model experiments with passive tracers, *J. Geophys. Res. Oceans*, *121*, 877–907, doi:10.1002/2015JC011290.

Enderlin, E. M., I. M. Howat, S. Jeong, M. . Noh, J. H. Van Angelen, and M. R. Van Den Broeke (2014), An improved mass budget for the Greenland ice sheet, *Geophys. Res. Lett.*, *41*, 866–872, doi:10.1002/2013GL059010.

Ferry, N., E. Greiner, G. Garric, T. Penduff, A.-M. Treiguier, and G. Reverdin (2008), GLORYS-1 Reference Manual for Stream 1 (2002–2007), *GLORYS Project Rep*.

Fichefet, T., and M. A. M. Maqueda (1997), Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, *J. Geophys. Res.*, *102*(C6), 12,609–12,646.

Fichefet, T., C. Poncin, H. Goosse, P. Huybrechts, I. Janssens, and H. Le Treut (2003), Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century, *Geophys. Res. Lett.*, *30*(17), 1911, doi:10.1029/2003GL017826.

Fratantoni, P. S., and M. S. McCartney (2010), Freshwater export from the Labrador Current to the North Atlantic Current at the tail of the Grand Banks of Newfoundland, *Deep Sea Res. Part I*, *57*(2), 258–283, doi:10.1016/j.dsr.2009.11.006.

Fratantoni, P. S., and R. S. Pickart (2007), The western North Atlantic shelfbreak current system in summer, *J. Phys. Oceanogr.*, *37*(10), 2509–2533.

Gillard, L. C. (2015), Ocean circulation and marine terminating glaciers of the Greenland ice sheet, Master's thesis, Univ. of Alberta, Edmonton, Alberta, Canada.

Grist, J. P., et al. (2014), Seasonal variability of the warm Atlantic water layer in the vicinity of the Greenland shelf break, *Geophys. Res. Lett.*, *41*, 8530–8537, doi:10.1002/2014GL062051.

Hanna, E., et al. (2013), Ice-sheet mass balance and climate change, *Nature*, *498*(7452), 51–59.

Hawkings, J., et al. (2016), The Greenland ice sheet as a hot spot of phosphorus weathering and export in the Arctic, *Global Biogeochem. Cycles*, *30*, 191–210, doi:10.1002/2015GB005237.

Holdsworth, A. M., and P. G. Myers (2015), The influence of high-frequency atmospheric forcing on the circulation and deep convection of the Labrador Sea, *J. Clim.*, *28*(12), 4980–4996.

Holland, D. M., R. H. Thomas, B. De Young, M. H. Ribergaard, and B. Lyberth (2008), Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters, *Nat. Geosci.*, *1*(10), 659–664.

Holliday, N. P., A. Meyer, S. Bacon, S. G. Alderson, and B. de Cuevas (2007), Retroflection of part of the East Greenland Current at Cape Farewell, *Geophys. Res. Lett.*, *34*(7), L07609, doi:10.1029/2006GL029085.

Holliday, N. P., S. Bacon, J. Allen, and E. L. McDonagh (2009), Circulation and transport in the western boundary currents at Cape Farewell, Greenland, *J. Phys. Oceanogr.*, *39*(8), 1854–1870, doi:10.1175/2009JPO4160.1.

Hu, X., and P. G. Myers (2013), A Lagrangian view of Pacific water inflow pathways in the Arctic Ocean during model spin-up, *Ocean Modell.*, *71*, 66–80, doi:10.1016/j.ocemod.2013.06.007.

Jackson, R. H., F. Straneo, and D. A. Sutherland (2014), Externally forced fluctuations in ocean temperature at Greenland glaciers in non-summer months, *Nat. Geosci.*, *7*(7), 503–508.

Lavender, K. L., R. E. Davis, and W. B. Owens (2000), Mid-depth recirculation observed in the interior Labrador and Irminger seas by direct velocity measurements, *Nature*, *407*, 66–69.

Li, Y., R. Ji, P. S. Fratantoni, C. Chen, J. A. Hare, C. S. Davis, and R. C. Beardsley (2014), Wind-induced interannual variability of sea level slope, along-shelf flow, and surface salinity on the Northwest Atlantic shelf, *J. Geophys. Res. Oceans*, *119*, 2462–2479, doi:10.1002/2013JC009385.

Lique, C., A. M. Treguier, B. Blanke, and N. Grima (2010), On the origins of water masses exported along both sides of Greenland: A Lagrangian model analysis, *J. Geophys. Res.*, *115*, C05019, doi:10.1029/2009JC005316.

Loder, J., B. Gawarkiewicz, and B. Petrie (1998), The coastal ocean of Northeastern North America (Cape Hatteras to Hudson Strait), in *The Sea: Ideas and Observations on Progress in the Study of the Seas*, vol. 11, edited by A. A. Robinson and K. Brink, pp. 1062, The Global Coastal Ocean, Regional Studies, Toronto.

Luo, H., R. M. Castelao, A. K. Rennermalm, M. Tedesco, A. Bracco, P. L. Yager, and T. L. Mote (2016), Oceanic transport of surface meltwater from the southern Greenland ice sheet, *Nat. Geosci.*, doi:10.1038/ngeo2708.

Madec, G. (2008), *NEMO Ocean Engine*, Note du Pole de modélisation 27, Institut Pierre-Simon Laplace (IPSL), France.

Marsh, R., D. Desbruyères, J. Bamber, B. De Cuevas, A. Coward, and Y. Aksenov (2010), Short-term impacts of enhanced Greenland freshwater fluxes in an eddy-permitting ocean model, *Ocean Sci.*, *6*(3), 749–760, doi:10.5194/os-6-749-2010.

Marsh, R., et al. (2015), Nemo-icb (v1.0): interactive icebergs in the NEMO ocean model globally configured at eddy-permitting resolution, *Geosci. Model Dev.*, *8*(5), 1547–1562, doi:10.5194/gmd-8-1547-2015.

Marshall, J. et al. (1998), The Labrador Sea deep convection experiment, *Bull. Am. Meteorol. Soc.*, *79*(10), 2033–2058.

Mauritzen, C. et al. (2011), Closing the loop—Approaches to monitoring the state of the Arctic Mediterranean during the International Polar year 2007–2008, *Prog. Oceanogr.*, *90*(1–4), 62–89, doi:10.1016/j.pocean.2011.02.010.

Melling, H. et al. (2008), *Arctic-Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate*, edited by R. Dickson, J. Meincke, and P. Rhines, Fresh-Water fluxes Via Pacific and Arctic Outflows Across the Canadian Polar Shelf, 193–247 pp., Springer, Dordrecht, Netherlands.

Myers, P. G. (2005), Impact of freshwater from the Canadian Arctic Archipelago on Labrador Sea water formation, *Geophys. Res. Lett.*, *32*(6), L06605, doi:10.1029/2004GL022082.

Myers, P. G., and M. H. Ribergaard (2013), Warming of the polar water layer in Disko Bay and potential impact on Jakobshavn Isbrae, *J. Phys. Oceanogr.*, *43*, 2629–2640.

Myers, P. G., C. Donnelly, and M. H. Ribergaard (2009), Structure and variability of the West Greenland Current in summer derived from 6 repeat standard sections, *Prog. Oceanogr.*, *80*(1–2), 93–112.

Rignot, E., and J. Mouginot (2012), Ice flow in Greenland for the International Polar year 2008–2009, *Geophys. Res. Lett.*, *39*, L11501, doi:10.1029/2012GL051634.

Robinson, A., R. Calov, and A. Ganopolski (2012), Multistability and critical thresholds of the Greenland ice sheet, *Nature Clim. Change*, *2*(6), 429–432.

Rykova, T., F. Straneo, and A. S. Bower (2015), Seasonal and interannual variability of the West Greenland Current System in the Labrador Sea in 1993–2008, *J. Geophys. Res. Oceans*, *120*, 1318–1332, doi:10.1002/2014JC010386.

Sasgen, I., M. van den Broeke, J. L. Bamber, E. Rignot, L. S. Sørensen, B. Wouters, Z. Martinec, I. Velicogna, and S. Simonsen (2012), Timing and origin of recent regional ice-mass loss in Greenland, *Earth Planet. Sci. Lett.*, *333–334*, 293–303, doi:10.1016/j.epsl.2012.03.033.

Shepherd, A. et al. (2012), A reconciled estimate of ice-sheet mass balance, *Science*, *338*(6114), 1183–1189.

Smith, G. C., F. Roy, P. Mann, F. Dupont, B. Brasnett, J.-F. Lemieux, S. Laroche, and S. Bélair (2014), A new atmospheric dataset for forcing ice-ocean models: Evaluation of reforecasts using the Canadian global deterministic prediction system, *Q. J. R. Meteorol. Soc.*, *140*(680), 881–894.

Straneo, F. (2006), Heat and freshwater transport through the central Labrador Sea, *J. Phys. Oceanogr.*, *36*(4), 606–628.

Straneo, F., and P. Heimbach (2013), North Atlantic warming and the retreat of Greenland's outlet glaciers, *Nature*, *504*(7478), 36–43.

Straneo, F., and F. Saucier (2008), The outflow from Hudson Strait and its contribution to the Labrador Current, *Deep Sea Res. Part I*, *55*(8), 926–946, doi:10.1016/j.dsr.2008.03.012.

Swingedouw, D., P. Braconnot, and O. Marti (2006), Sensitivity of the Atlantic Meridional Overturning Circulation to the melting from northern glaciers in climate change experiments, *Geophys. Res. Lett.*, *33*(7), L07711, doi:10.1029/2006GL025765.

Swingedouw, D., C. B. Rodehacke, S. M. Olsen, M. Menary, Y. Gao, U. Mikolajewicz, and J. Mignot (2014), On the reduced sensitivity of the Atlantic overturning to Greenland ice sheet melting in projections: A multi-model assessment, *Clim. Dyn.*, *44*(11), 3261–3279, doi:10.1007/s00382-014-2270-x.

Weijer, W., M. E. Maltrud, M. W. Hecht, H. A. Dijkstra, and M. A. Kliphuis (2012), Response of the Atlantic Ocean circulation to Greenland ice sheet melting in a strongly-eddying ocean model, *Geophys. Res. Lett.*, *39*(9), L09606, doi:10.1029/2012GL051611.

Yang, Q., T. Dixon, P. Myers, J. Bonin, D. Chambers, and M. R. van den Broeke (2016), Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation, *Nat. Commun.*, *7*, 10525, doi:10.1038/ncomms10525.