Meltwater Pathways from Marine Terminating Glaciers of the Greenland Ice Sheet

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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 timescale. 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 ($\sim$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 icesheet 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 metres [*Bamber et al.*, 2013] and could pass a threshold for the viability of the ice sheet for a temperature increase above pre-industrial of 3.1^{o}C [*Robinson et al.*, 2012]. The enhanced mass loss from the GrIS comes from a combination of factors including: 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] (Fig.1). 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).

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: 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 (NADW) [*Weijer et al.*, 2012], feeding the Atlantic Meridonal 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 bouyant 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 westwards.

Here we will examine the eventual fate of the Greenland meltwater as it is taken up within the sub-polar gyre and Baffin Bay over longer timescales. 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 timescales.

2. Methods

To examine the fate of a specific water mass, we used a well tested [*Lique et al.*, 2010; *de Boissson 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 (3D) 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^oS. The configuration's mesh grid is extracted from a global tripolar grid, ORCA [*DRAKKAR et al.*, 2007]. ANHA4 has a $1/4^o$ horizontal grid with resolution ranging from $\sim$5.79km in Northern Canada to $\sim$27.9km at the equator. ANHA12 has a $1/12^o$ horizontal resolution, with a resolution of $\sim$1.93km near the artificial pole over Northern Canada and $\sim$9.3km 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 Morales 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 (CMC) global deterministic prediction system (GDPS) reforcasts (CGRF) dataset [*Smith et al.*, 2014] has hourly 33km resolution for the following fields: 10 metre surface wind, 2 metre 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) velocity fields for years 2002-2010 for ANHA4 and ANHA12 for each of the 5 sectors (shown in Fig.1 and listed in Table S1) 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 Fig.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 ($\sim$1000) were homogeneously distributed in space in the first 21 model grid levels of the water column (77.85 metres) 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 are 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 5 sectors of the GrIS (Fig.1). One representative glacier is chosen for each region. Results for additional glaciers in each region are given in the supplementary information.

Surface freshwater by the outlet region of Petermann Glacier (PG) (Fig.2.1) has a high probability to head south through Nares Strait at surface and subsurface depths and enter Baffin Bay interior at sub-intermediate 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 waters 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) suggests 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 (DB) (Fig.2.2) and Julianehab (JUL) (Fig.2.3), as results for other glaciers in the west sector behave similarly (Fig.S1.2, Fig.S1.3, Fig.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) (Fig.2.4), which has similar behaviour to all the southeast outlet regions and as well as several from north of Denmark Strait, including Kangerdlugssuaq (KGLQ), Kong Christian IV (KCIV) and ScoresbySund (SBS) (Fig.S1.5, Fig.S1.6, Fig.S1.7). There is a tongue of high probability in the EGC/WGC, as the particles (and freshwater) are swept away within one 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]; *Rykova et al.* [2015]), occurring within the first year.

Surface waters found by the northeast outlet regions of Nioghalvfjerdsfjorden (79NG) (Fig.2.5) (similarly Zachariae Isstrom (ZI), Fig.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, four to five years after release, with little exchange offshore north of the Grand Banks (especially in ANHA12).

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] except defining 5 passive tracers for the different regions of coastal Greenland (Fig.3.a). As discussed in greater detail in that paper [*Dukhovskoy et al.*, 2016], passive tracers are released from January 1, 2004, proportional to the amount of runoff from Greenland at each timestep, and each grid cell.

Integrated concentrations of the passive tracer after 7 years (the end of 2010) are shown for the southwest (Fig.3.c) and southeast (Fig.3.d) tracer release locations. In general, the tracer field is consistent with ARIANE. The tracer released from southwest Greenland (Fig.3.c) 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 (Fig.3.d). 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 on Fig.3.a), 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 metre isobath and includes the region where deep convection occurs (given on Fig.1). This confirms the picture from ARIANE and the passive tracer concentration maps. As seen in Fig.3.d, 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 Fig.3.b 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 (Fig. S2). This is consistent with a more idealized modelling study [*Castro de la Guardia et al.*, 2015] and supports their contention that circulation within Baffin Bay and the exchange through the CAA is 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, Fig.2.4 and Fig.3.d) more easily reach the interior of the Labrador Sea. This occurs both due to exchange from the WGC, and also do to circulation around the Labrador Sea. The exchange from the WGC is rapid, occurring within 6 months of release (Fig. 2, S2). As the particles are farther offshore along a deeper isobath, they recirculate back to the north (Fig. 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 timescales, 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 behaviour.

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 timescales. 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 timescales 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.

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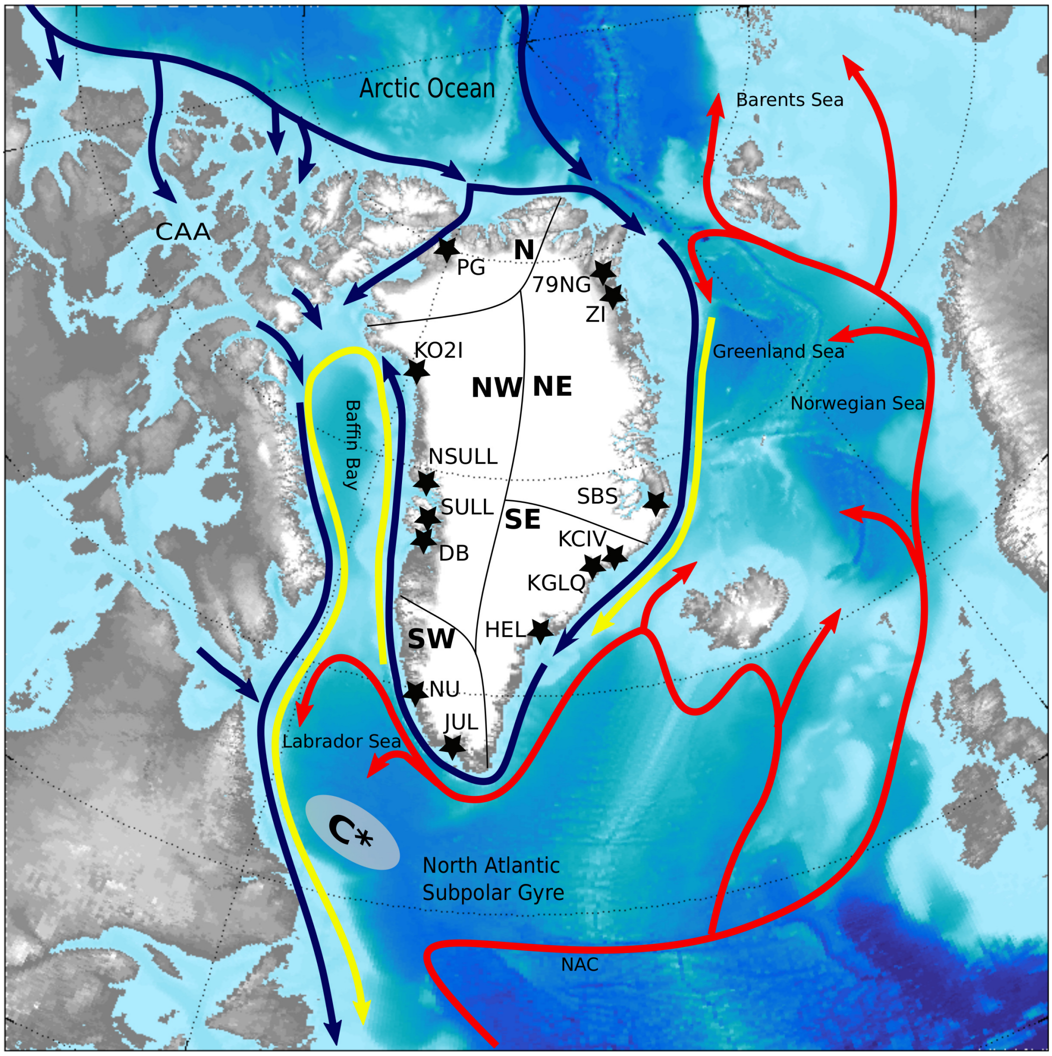
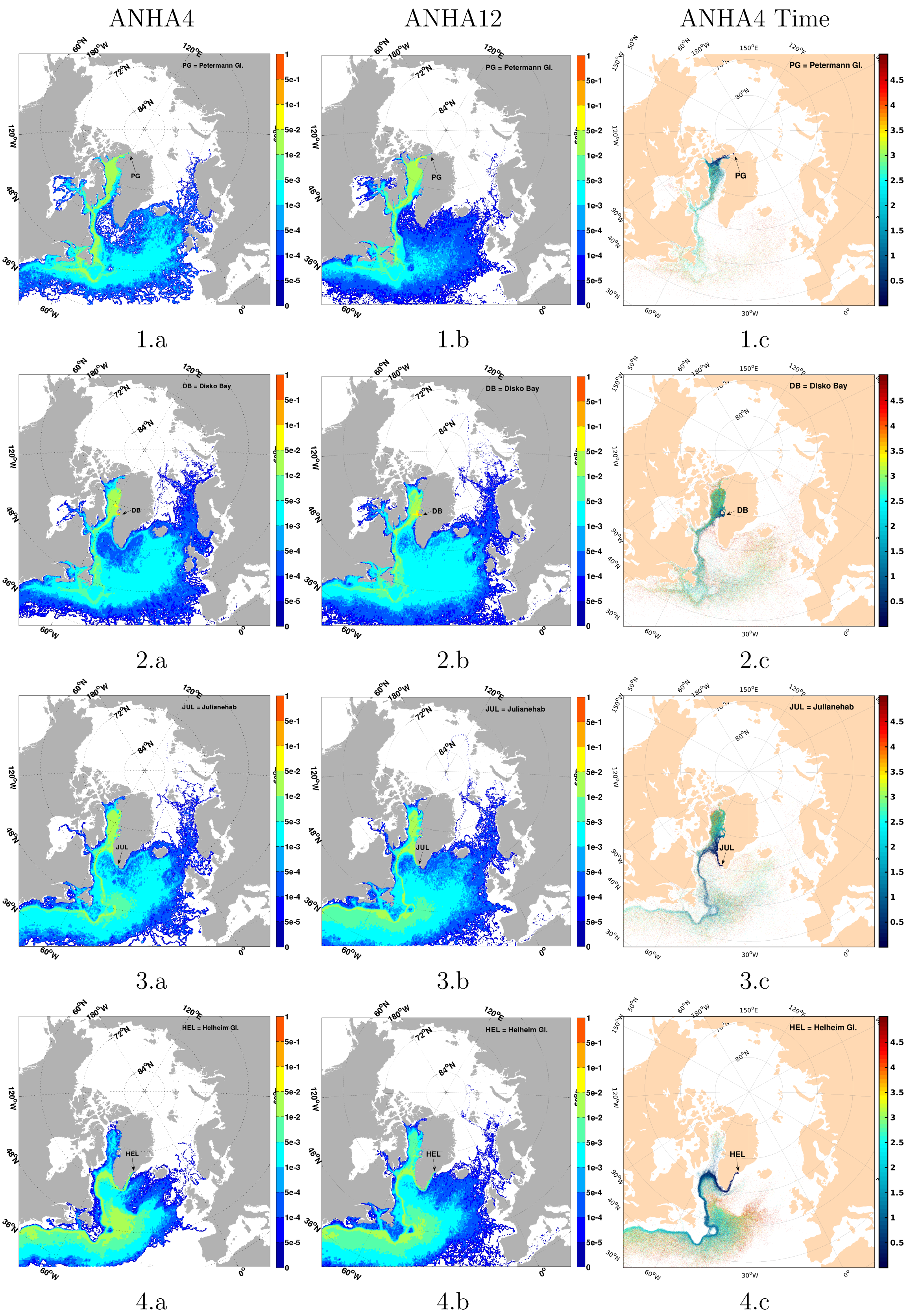


Figure 1. Ocean Circulation around Greenland and 13 outlet regions along the Greenland Ice Sheet. Relatively warm Atlantic waters are seen in red and, the yellow dashed lines represent the mixed and cooled Atlantic waters. Arctic water and freshwater pathways are shown in blue dashed lines. The Labrador 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.


ANHA4
ANHA12
ANHA4 Time
PG = Petermann Gl.
PG
DB = Disko Bay
DB
JUL = Julianehab
JUL
HEL = Helheim Gl.
HEL
1.a
1.b
1.c
2.a
2.b
2.c
3.a
3.b
3.c
4.a
4.b
4.c

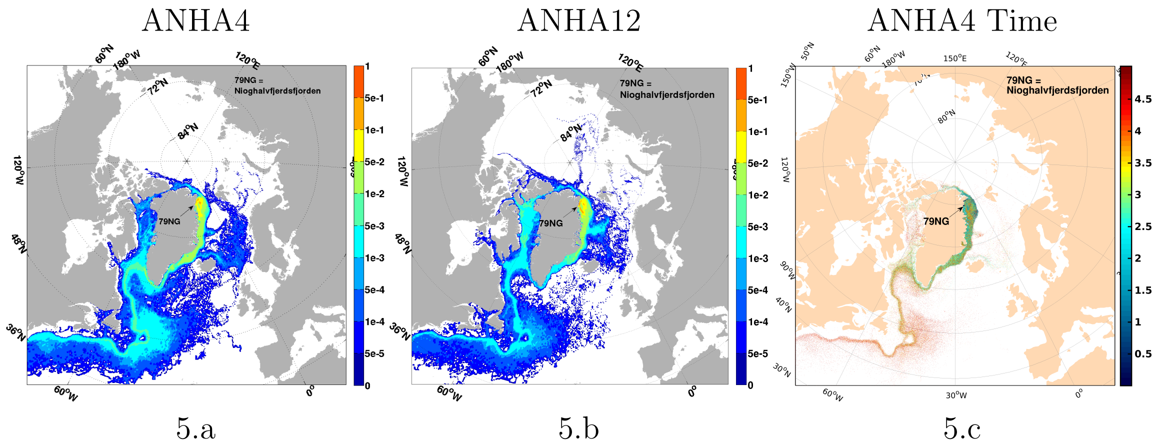


Figure 2. Forward transport of ARIANE virtual particles at selected outlet regions. Every row shares a similar outlet region, noted by the arrow in the figure with the full name on the top right hand side of the figure. Each column separates the outlet region by the 2 experiments (ANHA4 and ANHA12 respectively) and a time evolution analysis of ANHA4. This figure contains 1 outlet region for the 5 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 metres). 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 of the virtual particles from the ANHA4 experiment. For an analysis on the other 8 outlet regions see Fig. S1.

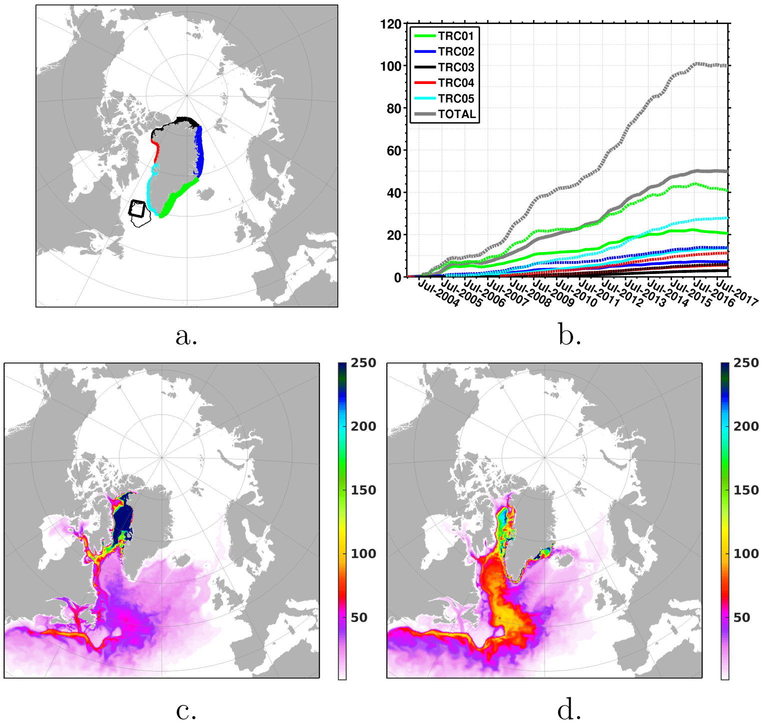


Figure 3. 5 passive tracers for different regions along the coast of Greenland. Passive tracers are released from January 1, 2004, proportional to the amount of runoff from Greenland at each timestep, and each grid cell. (a): Shows the location of five passive tracers, corresponding to the location of freshwater input. The thick black box shows the location of the central Labrador Sea and the thin black polygon outlines the 3000 metre deep central basin. (b): Shows the evolution of central Labrador Sea tracer storage (solid line for the central Labrador Sea and dashline for the deep basin in Fig.3.a) 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, colour in cyan in Fig.3.a,b) 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 colour in Fig.3.a,b) by the end of 2010.