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Potential positive feedback between Greenland Ice Sheet melt and Baffin Bay heat content on the west Greenland shelf

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Key Points:

- Enhanced melt of Greenland increases heat content on the west Greenland shelf
- Enhanced melt of Greenland reduces CAA volume flux
- Enhanced melt of Greenland strengthens the cyclonic circulation in Baffin Bay

Supporting Information:

- Texts S1–S6, Figures S1–S7, and Table S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5

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Abstract Greenland ice sheet meltwater runoff has been increasing in recent decades, especially in the southwest and the northeast. To determine the impact of this accelerating meltwater flux on Baffin Bay, we examine eight numerical experiments using an ocean-sea ice model: Nucleus for European Modelling of the Ocean. Enhanced runoff causes shoreward increasing sea surface height and strengthens the stratification in Baffin Bay. The changes in sea surface height reduces the southward transport through the Canadian Arctic Archipelago and strengthens the gyre circulation within Baffin Bay. The latter leads to further freshening of surface waters as it produces a larger northward surface freshwater transport across Davis Strait. Increasing the meltwater runoff leads to a warming and shallowing of the west Greenland Irminger water on the northwest Greenland shelf. These warmer waters can now more easily enter fjords on the Greenland coast and thus provide additional heat to accelerate the melting of marine-terminating glaciers.

1. Introduction

Baffin Bay is a semienclosed water body bounded by Greenland on the east, Baffin Island on the west, the Canadian Arctic Archipelago (CAA) to the north, and Davis Strait to the south (Figure 1a). Within the basin, the circulation is cyclonic, and the waters are a mix of relatively warm and saline Atlantic water, cold and low-salinity Arctic water, and meltwater from the Greenland ice sheet.

The Atlantic-origin waters enter Baffin Bay at depths of 200–600 m in the northward flowing west Greenland slope current through eastern Davis Strait [*Tang et al.*, 2004; *Curry et al.*, 2011; *Azetsu-Scott et al.*, 2012; *Curry et al.*, 2014]. Within Baffin Bay, this inflow forms a warm subsurface layer that is hereafter referred to as the west Greenland Irminger water (WGIW).

Near the surface (depths ranging 30–200 m), flowing over the west Greenland shelf and slope, is the West Greenland Current (WGC) carrying modified Arctic water that exited the Arctic Ocean through Fram Strait [*Tang et al.*, 2004; *Myers and Ribergaard*, 2013; *Curry et al.*, 2014]. However, the main source of Arctic water into Baffin Bay is through the three channels of the CAA: Nares Strait, Jones Sound, and Lancaster Sound [*Tang et al.*, 2004; *Curry et al.*, 2014]. The Arctic water entering through the CAA is colder than Arctic water in the WGC [*Gladish et al.*, 2015].

The meltwater signal from the Greenland ice sheet is found in the upper 30 m of the water column. It enters Baffin Bay as glacier melt and icebergs that break off the tongue of marine-terminating glaciers [*Tang et al.*, 2004]. Typically, glaciers in Greenland end in fjords which can be more than 800 m deep but have sill depths ranging from 150 to 250 m at the mouth of the fjord [*Johannessen et al.*, 2011; *Myers and Ribergaard*, 2013; *Gladish et al.*, 2015]. The circulation within a fjord is driven by the basal melting and subglacial discharge, and it is separated from the larger-scale circulation of Baffin Bay by the sill [*Rignot et al.*, 2010; *Straneo et al.*, 2010; *Johannessen et al.*, 2011; *Straneo and Heimbach*, 2013; *Gladish et al.*, 2015].

This in-fjord circulation constitutes a major difference between Greenland and Antarctica in regard to how the meltwater from the glaciers interact with the nearby ocean circulation. In Antarctica, the ice shelves, which drain 80% of the ice sheet, are in contact with the large-scale ocean circulation [*Pritchard et al.*, 2012]; thus, mixing due to glaciers melting at depth could have an impact on the ocean at large. In Greenland, however, mixing and entrainment due to glaciers melting at depths happen within the fjords [*Rignot et al.*, 2010; *Straneo et al.*, 2010; *Johannessen et al.*, 2011; *Straneo and Heimbach*, 2013; *Gladish et al.*, 2015].

In Greenland, the low-salinity water from glaciers melting at depth rises within the fjord and then flows out of the fjord as a surface current [*Rignot and Steffen*, 2008; *Rignot et al.*, 2010; *Motyka et al.*, 2011; *Straneo and*

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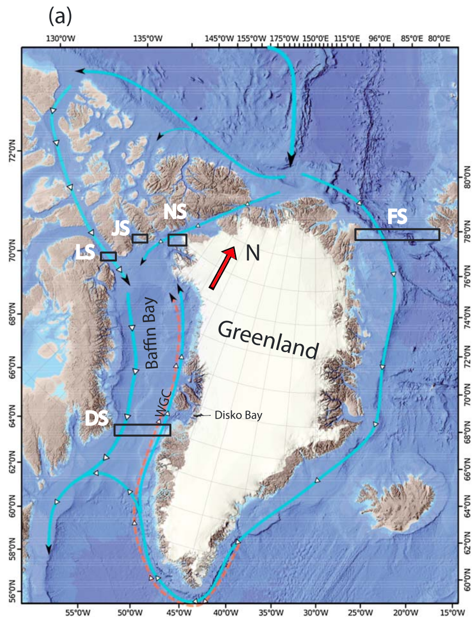

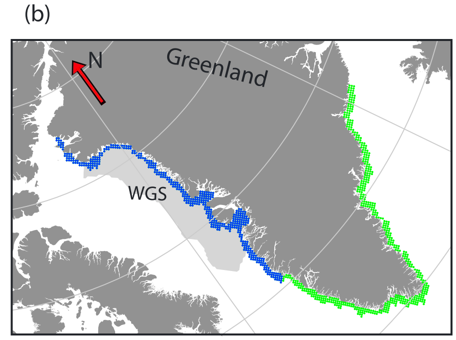

Experiment	Runoff (km^3/year)	Runoff zone	Seasonality
runoff00	31.5	all shelf	ideal
runoff158	158	blue	ideal
runoff158s	158	blue	realistic
runoff254	254	blue	ideal
runoff398	398	blue	ideal
runoff788	788	blue	ideal
runoff788b	788	blue & green	ideal
runoff1000	1000	blue	ideal
runoff1580	1580	blue	ideal

Figure 1. Study area and experiment setup. (a) A generalized representation of the general circulation within Baffin Bay and water exchanges. Circulation through the Canadian Arctic Archipelago (CAA, group of islands to the west of Baffin Bay) regulates the exchanges between Arctic Ocean and Baffin Bay. Cold Arctic waters enter Baffin Bay through Lancaster Sound (LS), Jones Sound (JS), and Nares Strait (NS) (black boxes). Arctic water exiting through Fram Strait (FS) also enters Baffin Bay through Davis Strait (DS) in the upper 200 m of the West Greenland Current (WGC). Warm Atlantic water enters Baffin Bay through DS at depth (below 200 m) in the WGC (red dash line). (b) Experiments are set up with runoff added on the northwest Greenland coast (blue-shaded area). Experiment runoff788b includes, in addition to runoff in the northwest, runoff along the southwest and southeast coasts (green-shaded area). Calculations of temperature and heat content of the west Greenland shelf (WGS) are done by integrating the temperature and heat changes within the gray-shaded region. A list of the experiments is presented with details about the setup.

Heimbach, 2013]. This drives a return flow at depth, which in Baffin Bay is near the depth range of the WGIW [*Holland et al.*, 2008; *Loyd et al.*, 2011; *Myers and Ribergaard*, 2013]. The sill at the mouth of the fjords is the only obstacle to warm shelf waters entering a fjord and contributing to the melting of tidewater glaciers [*Holland et al.*, 2008; *Rignot et al.*, 2010; *Straneo et al.*, 2010; *Johannessen et al.*, 2011; *Straneo and Heimbach*, 2013; *Myers and Ribergaard*, 2013; *Gladish et al.*, 2015]. In this framework, marine-terminating glaciers in northwest Greenland are exposed to rising Atlantic Ocean temperatures and the associated changes in the WGIW heat content [*Rignot and Steffen*, 2008; *Rignot et al.*, 2010; *Myers and Ribergaard*, 2013].

In recent decades and coincident with warmer subsurface waters entering the fjords, there has been an acceleration in the melting rate of northwest Greenland glaciers [*Holland et al.*, 2008; *Motyka et al.*, 2011; *Straneo and Heimbach*, 2013; *Myers and Ribergaard*, 2013]. In anticipation of further melt from the Greenland ice sheet [*Church et al.*, 2013], further study of how Baffin Bay shelf waters may respond to enhanced meltwater production is warranted. Previous studies showed that increased meltwater discharge from Greenland reduces the CAA throughflow and freshens the surface waters in Baffin Bay within 5 years [*Rudels*, 2011; *Brunnabend et al.*, 2012]. The Arctic inflow through the CAA is a large source of cold water; thus, it has an important cooling effect on Baffin Bay. The freshening of surface waters stabilizes the near-surface water column, which reduces vertical mixing and heat loss by the warmer subsurface water [*Brunnabend et al.*, 2012]. Based on these findings, we hypothesize that increasing runoff from Greenland could decrease heat loss from subsurface waters, which could favor the warming of the WGIW in Baffin Bay.

To test our hypothesis, we set up eight freshwater sensitivity experiments using the ocean-sea ice model Nucleus for European Modelling of the Ocean (NEMO) [*Madec and the Nucleus for European Modelling of the Ocean team*, 2008] for a wide range of meltwater discharge (Figure 1b). Icebergs also contribute to the Greenland ice sheet discharge into Baffin Bay [*Tang et al.*, 2004]. However, due to the numerical cost involved in coupling in an iceberg model, combined with the fact that most of the iceberg melt will occur within the boundary current (i.e., same as for the runoff we apply) or south of Davis Strait [*Tang et al.*, 2004], we begin examining this question without directly including an iceberg model.

2. Methods

2.1. Model Details

All simulations were carried out with the coupled ocean-sea ice model, Nucleus for European Modelling of the Ocean (NEMO) [*Madec and the Nucleus for European Modelling of the Ocean team*, 2008], using a regional configuration covering the northern Bering Sea, Arctic Ocean, CAA, Nordic seas, and North Atlantic Ocean north of 45°N [*Hu and Myers*, 2013]. Our configuration has variable horizontal resolution ranging from 11 km in the central CAA to 15 km in the Arctic Ocean and has 46 vertical levels. In Baffin Bay, the horizontal resolution is 12 km. The model is initialized with the Polar Science Center Hydrographic Climatology 3.0 [*Steele et al.*, 2001] and forced with version 2 forcing of the Coordinated Ocean-ice Reference Experiment (CORE2) normal year forcing [*Large and Yeager*, 2004] (see Figure S1 in the supporting information for precipitation field). There is no surface relaxation for either temperature or salinity, which is important for ensuring that the freshwater signal from Greenland is not dampened [*Marsh et al.*, 2010]. Open boundary data are taken from a global 0.25° hindcast using the NEMO model [*Barnier et al.*, 2006].

2.2. Experiment Setup

To carry out the eight Greenland meltwater sensitivity experiments, we selected a range of runoff to bracket observed Greenland freshwater discharge as well as potential future loss. The experiments with lower runoff input, 158 km^3 yr^{-1} and 294 km^3 yr^{-1} to 394 km^3 yr^{-1}, are close to current estimates of Greenland ice sheet freshwater discharge. For example, for the period 1996–2008, *van den Broeke et al.* [2009] estimated that the total amount of meltwater runoff from Greenland was ~1500 km^3, yielding ~131.7 km^3 yr^{-1}. In western Greenland, *Mernild and Liston* [2012] estimated that the five decade mean (1960–2010) freshwater runoff was 11,850 km^3, yielding a ~237.0 km^3 yr^{-1} average. A recent modeling study suggested a northwest Greenland freshwater flux of ~350 km^3 yr^{-1} between 2005 and 2010 [*Bamber et al.*, 2012]. Our experiments with larger inputs, 788 km^3 yr^{-1}, 1000 km^3 yr^{-1}, and 1580 km^3 yr^{-1}, are designed to represent a future where the meltwater runoff from the Greenland ice sheet has increased significantly.

We added the meltwater into the first model level (which is 6 m thick) and include enhanced mixing of the runoff into the second level (10 m). With this setting, we can focus on what happens once the meltwater leaves the fjords to enter Baffin Bay. The mixing and entrainment caused by ice melting at depth occurs within the fjords of Greenland, and the circulation within the fjords are such that the meltwater exits the fjords as surface flow [*Holland et al.*, 2008; *Rignot et al.*, 2010; *Straneo et al.*, 2010; *Johannessen et al.*, 2011; *Mortensen et al.*, 2011; *Myers and Ribergaard*, 2013]. This is different from Antarctica where the ice shelves are in direct contact with the ocean [*Pritchard et al.*, 2012], and melting at depth can have an effect on the large-scale circulation.

In all experiments, the meltwater was added each year along the northwest Greenland coast uniformly as a constant flux (Figure 1b). We attempted to capture the near-uniform distribution of runoff along the Greenland coast given by a recent Greenland ice sheet model [*Bamber et al.*, 2012] (Figure S2). The meltwater was added in the first two model cells closest to the coast, thus distributing the runoff up to 24 km offshore. By doing so, we incorporate, to some degree, the advective effect on the freshwater flux by icebergs which transports meltwater offshore [*Martin and Adcroft*, 2010; *Yankovsky and Yashayaev*, 2014].

Martin and Adcroft's [2010] global simulation using an iceberg parametrization shows that the meltwater from drifting icebergs builds up along all the northwest Greenland shelf with an increasing gradient from the center of Baffin Bay to the northwest shelf [see *Martin and Adcroft*, 2010, Figure 2]. Meltwater from icebergs drifting also reduces the salinity as far as northern Baffin Bay [see *Martin and Adcroft*, 2010, Figure 4]. They suggest that to achieve these results, one could distribute the runoff with an "invariant pattern" which would reduce the computational cost of explicitly including the iceberg model. In our simulations, by equally distributing the runoff along the model coastline (at the fjords mouth when fjords were present), we accomplished a similar effect as the meltwater is rapidly picked up by the boundary current and distributed throughout the shelf.

Of course there are limitations to this approach. Drifting icebergs are associated with small-scale (2–4 km) dynamic processes (e.g., buoyancy plumes) that enhance mixing between surface and subsurface layers and may persist for several days [*Yankovsky and Yashayaev*, 2014]. Also, much of the freshwater flux from icebergs in Baffin Bay is transported into the Labrador Sea [*Martin and Adcroft*, 2010] since icebergs melt more commonly south of Davis Strait [*Tang et al.*, 2004]. As a result, our simulations will tend to accumulate more freshwater in the surface layers and more heat in the subsurface layers compared to an identical simulation that parametrizes icebergs. However, by using a high-resolution model (~12 km), we can resolve the mesoscale dynamics which are missed in coarse resolution models (1° by 1°) such as *Martin and Adcroft's* [2010] global model.

To consider the importance of spatial distribution of the runoff around Greenland, we added the meltwater also along the southwest and southeast coast of Greenland in *runoff788b* (Figure 1b). This experiment was designed to test if increasing meltwater runoff in southern Greenland affects Baffin Bay. This is important, because the discharge in the southeast amounts for half of the total Greenland mass loss between 2003 and 2008 [*van den Broeke et al.*, 2009]. Also, results from a Greenland ice sheet model show that both the southeast and northwest have had more rapid increase in freshwater discharge in recent years (1995–2010) [*Bamber et al.*, 2012].

We assume an ideal seasonal cycle and constant melting rate, and we evenly distributed runoff between May and October each year. To test the effect of seasonality, we ran experiment *runoff158s* with a more realistic seasonal cycle by adding meltwater runoff with different weight for each month: 3% in May and October, 10% in June and September, and 38% in July and August. We use a control experiment (*runoff00*) for comparison with the eight sensitivity experiments to highlight the impact of the enhanced runoff. The runoff data for our control experiment (total discharge < 31.5 km^3 yr^{-1}) was obtained by linearly interpolating a $1 \times 1°$ gridded monthly runoff climatology to our configuration [*Dai et al.*, 2009].

Each of our experiments ran for 10 years. This period was long enough for the initial transient behavior to level off and show clear impacts of the enhanced Greenland melt on Baffin Bay [*Brunnabend et al.*, 2012]. All our calculations used the last 5 years of the simulations (model years 6 to 10), and for comparisons, we use the anomaly calculated as the difference between the meltwater experiment and the control run. The heat content was calculated using a reference temperature of 0°C. We used the Pearson's correlation coefficient (R) to evaluate linear relationships across time and experiment.

3. Results

A comparison between experiments with equal amounts of runoff but different seasonality (i.e., *runoff158* and runoff158s) shows similar hydrographic response in Baffin Bay (Figure S3). This suggests that our ideal seasonal cycle is sufficient for examining the mean annual response of Baffin Bay to enhanced runoff. Including meltwater discharged in southern Greenland caused comparably larger hydrographic response (i.e., *runoff788* and runoff788b), although the physical explanation for the response remained similar across experiments. For clarity of the presentation, we follow with a discussion of the results of experiments with enhanced runoff in northwest Greenland, leaving for later the discussion of the impact of regional extent of meltwater discharged in experiment runoff788b.

3.1. Sea Surface Height and Circulation Changes

Enhanced meltwater runoff from the northwest Greenland ice sheet leads to a progressive decrease in surface (0–200 m) salinity along the northwest coast of Greenland (Figure 2a) that is accompanied by large sea surface height changes in Baffin Bay (Figures 2b–2e). Sea surface height increases more prominently along the boundary current and within the channels in the CAA. The largest increase in sea surface height (up to 20 cm) are along the Greenland shelf. This steepens the sea surface height gradient between the coast and the center of the Bay which leads to a strengthening of the east branch of the cyclonic gyre in Baffin Bay: the WGC (Figure 2a). A stronger WGC causes a positive feedback that reduces salinity in Baffin Bay as more freshwater is imported through Davis Strait in the surface layers (0–150 m) (Figures 2a and S4b).

The higher sea surface height in northwestern Baffin Bay and the CAA shoals the sea surface height gradient between the Arctic Ocean and Baffin Bay which causes a reduction in the net Arctic water flux through the CAA ($R = -0.88$ and $p < 0.01$). Previous studies have also found a strong correlation between transport through the CAA and the sea surface height gradient between Baffin Bay and the Arctic Ocean [*Kliem and Greenberg*, 2003; *Rudels*, 2011; *McGeehan and Maslowski*, 2012; *Hu and Myers*, 2014]. Other factors such as winds in the Beaufort Sea may also influence the interannual variability of this transport when atmospheric variability is present [*Peterson et al.*, 2012]. Atmospheric variability is removed in our simulations by using CORE2 perpetual year forcing.

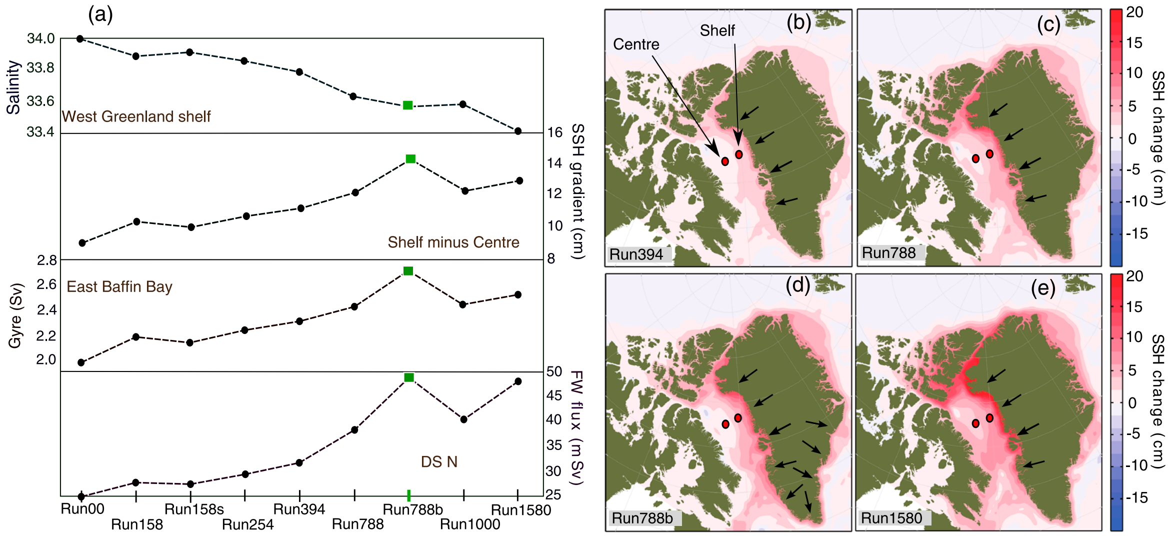

Figure 2. (a) Mean response of Baffin Bay salinity, sea surface height (SSH) gradient, circulation/gyre strength, and northward David Strait (DS N) freshwater (FW) fluxes to increasing meltwater runoff from Greenland. The mean is calculated over the last 4 years of the simulation. Salinity changes are calculated over the west Greenland shelf (WGS) region defined in Figure 1. The SSH gradient between the shelf region and the center of the Baffin Bay is calculated using SSH difference between the two red dots in Figures 2b–2e (and highlighted in Figure 2b by the two long arrows). The gyre strength is the depth-integrated flux across these two red dots. The green square marker on the line plots highlights experiment runoff788b with freshwater input on all of southern and western Greenland. (b–e) The SSH anomaly relative to the control run for the last year of the simulation. Red and pink colors represent an increase in SSH relative to the control run. An abbreviated name label for each experiment shown is at the bottom left corner of each panel, with the number indicating the total amount of meltwater added per year in cubic kilometer. The small arrows indicate the region where runoff was added.

In our simulations, the annual mean transport through the CAA into Baffin Bay is reduced by 0.2 Sv (Sverdrup = 10^6 m^3/s) to 0.6 Sv, from experiment runoff158 to experiment *runoff1580*, respectively (Figure 3a). This corresponds with a 7% to 46% reduction in the mean freshwater flux (Table S1). The reduced transport through the CAA is balanced by a larger freshwater flux through Fram Strait ($R = -0.998$ and $p < 0.01$) (Table S1). Therefore, mean changes in the net freshwater exiting the Arctic Ocean were small (< 6%). This compensation was only 80–90% complete, suggesting that freshwater might be stored in the Arctic Ocean. Ice volume fluxes through the CAA also decline with increasing runoff (Figure S5).

The signal of the simulated circulation changes within Baffin Bay is detected at Davis Strait as a small reduction in the southward transport of Arctic water (0–250 m) ranging from 0.2 Sv to 1.2 Sv for runoff158 to runoff1580, respectively. Mooring data at Davis Strait [*Curry et al.*, 2014] for the periods 2004–2010 and 1987–1990 show a similar change (∼ 0.5 Sv) in the transport of Arctic water as in experiment *runoff394* (∼ 0.6 Sv). For the same time periods, the mooring data also shows an increase (by ∼0.6 Sv) in the inflow of warmer WGIW across Davis Strait. In our simulation, the northward volume and heat flux through Davis Strait does not change significantly in the depth range of the WGIW ($\triangle_{volume} = \sim 0.02$ Sv and $\triangle_{heat} = \sim 0.5$ TW; Figure S4).

Meanwhile, the strengthening of the cyclonic gyre in Baffin Bay causes stronger Ekman pumping that lifts the isopycnals in the center of the Bay (Figure S6) and causes the shallowing of the WGIW (defined by $T \geq 1.5$°C and $S \geq 34.1$ [*Tang et al.*, 2004; *Curry et al.*, 2014]) (Figure S7). The upper interface of the WGIW lifts to a depth less than 200 m throughout most of Baffin Bay in response to increasing runoff (Figures 3b–3e). On the northwest Greenland shelf, the upper interface of the WGIW shallows to a mean depth of 100 m and appears in areas of northern Baffin Bay where it was not previously present. From these shallower depths, the warm WGIW could more easily overflow the sills and penetrate coastal fjords providing heat to melt the marine-terminating glaciers in the region [*Gladish et al.*, 2015].

3.2. Temperature and Heat Content

Resulting from the changes in circulation and stratification, temperature and heat content on Greenland's northwest shelf increase progressively as a function of enhanced runoff (Figure 3a). The surface (0–200 m) temperature on the shelf increases by 0.2°C in experiment runoff394 and by 0.5°C in the strongest runoff experiment, runoff1580, relative to the control run. In the subsurface (150–600 m), temperatures warm by 0.3°C in runoff394 and by 0.5°C in runoff1580.

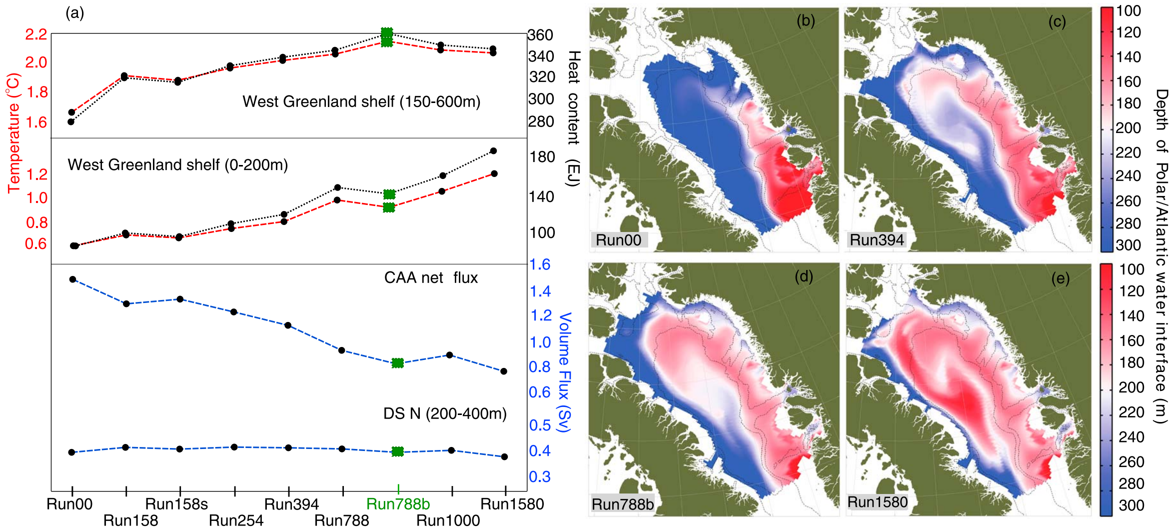

Figure 3. (a) Mean response of temperature and heat content in the west Greenland shelf (WGS) region (for definition of WGS, see Figure 1), and fluxes into Baffin Bay through Canadian Arctic Archipelago (CAA) and David Strait (DS) to increasing amounts of runoff from the Greenland ice sheet. The green square marker on the line plots highlights experiment runoff788b with runoff on all southern and western Greenland. (b–e) The depth of the interface between the warm west Greenland Irminger water (WGIW) and the cold polar water in response to increasing meltwater runoff from Greenland. The transition from blue to red indicates a shallowing of this interface and thus a shallowing of the WGIW. An abbreviated label for the experiments is at the bottom left corner of each panel, with the number in the label indicating the total amount of meltwater added per year in cubic kilometer.

Similar temperature trends for shelf waters were detected in Baffin Bay between 1928 and 2000, although these were associated with an increased inflow of warmer Atlantic water across Davis Strait [*Zweng and Münchow*, 2006]. The authors suggested that shelf waters have warmed by 0.15 $\pm$ 0.08°C decade^{-1} and the subsurface waters by 0.23 $\pm$ 0.13°C decade^{-1}. These values are closest to the changes we see in experiment runoff394, which has meltwater discharge most similar to present-day estimates of runoff from northwest Greenland [*Bamber et al.*, 2012].

The heat content of the surface layers (0–200 m) and the WGIW (150–600 m) on the shelf increases by 55 EJ in runoff394 and by 65 EJ in runoff1580, compared to the control run (Figure 3a). In Disko Bay, located in southern Baffin Bay (Figure 1), observations between 1977–1990 and 1996–2008 show increasing heat content [*Myers and Ribergaard*, 2013] for both polar water (0–200 m) and the WGIW (200–600 m). The authors suggested that the changes in heat content in eastern Baffin Bay were associated with changes in lateral exchanges which are impacted by the CAA inflow.

This hypothesis was supported by a recent study in which the authors [*Gladish et al.*, 2015] found that temperature changes within fjords opening to Disko Bay (i.e., Ilulissat fjord) are largely controlled by the fraction of polar water reaching the shelf. They described two types of polar water: a colder polar water with CAA origin and a warmer polar water with WGC origin. They suggested that the fraction of cold versus warm polar water entering Disko Bay is affected by the relative strength of these inflows (e.g., in 2010, colder waters in Disko Bay were associated with stronger CAA inflow and weaker WGC).

We agree with these studies in that warming of Greenland shelf waters could be associated with changes in Baffin Bay circulation. However, based on our sensitivity experiments, we think that these changes are also influenced by the recent accelerated melt of Greenland glaciers. In our simulations, increasing heat content on the northwest Greenland shelf is shown to result mostly from decreasing inflow of cold Arctic waters through the CAA (Figure 3a) and decreases in ocean heat exchange due to the stronger density stratification (Figure S6). *Brunnabend et al.* [2012] found that a stronger halocline would lead to decreased heat exchange between the surface and subsurface layers in Baffin Bay. Meanwhile, a reduced Arctic water inflow through the CAA negatively affects the lateral heat loss. The main heat source in Baffin Bay is warm Atlantic water entering through Davis Strait at depths below 200 m [*Curry et al.*, 2014], but this transport remains unchanged across experiments (Figures 3a and S4).

3.3. Experiment Runoff788b

In experiment runoff788b, meltwater runoff was added over an extended region from the northwest to the southeast coast of Greenland. We obtained a qualitatively similar response in Baffin Bay as described previously, but the amplitude was larger. As in the other experiments, in runoff788b, salinity drops along the Greenland coast, and the sea surface height gradient between the coast and the center of the basin increases.

However, because runoff is added over an extended region, both the west and the east Greenland currents strengthened, leading to a larger northward freshwater transport (0–200 m) through Davis Strait (+10 mSv) and stronger Baffin Bay gyre (+0.3 Sv), relative to runoff788 (Figures 2a and S4). The larger transport through Davis Strait brings into Baffin Bay the meltwater runoff that was added on the southeast and southwest coast of Greenland. Therefore, even when the total freshwater runoff per year added directly into Baffin Bay in runoff788b is approximately half of that added in runoff788, there is a similar response in terms of mean Baffin Bay sea surface height and net volume transport through the CAA (Figures 2 and 3).

An important difference in this experiment compared to its twin (runoff788) is a larger heat transport through Davis Strait (+0.2 TW, 200–400 m) that increases the heat content (+20 EJ) and temperature (+0.1°C) of the WGIW (150–600 m) on the west Greenland shelf (Figure 3a). These highlight the importance of including meltwater from all glaciers in Greenland and not only those draining directly into Baffin Bay.

4. Discussion

In this paper, we test the hypothesis that warming of subsurface waters in Baffin Bay is linked to accelerated Greenland glacier discharge. We set up eight enhanced meltwater sensitivity experiments using the ocean-sea ice model, NEMO. The enhanced melt led to changes in circulation, freshwater and heat fluxes in Baffin Bay. The meltwater runoff increased the stratification and raised the sea surface height. The sea surface height gradient between Greenland coast and the center of the Bay steepened, causing a stronger WGC which positively fed back to enhance the northward freshwater transport across Davis Strait. At the same time, the stronger gyre within Baffin Bay increased Ekman pumping and shoaled the isopycnals near the shelf, bringing warmer WGIW closer to the surface.

The higher sea surface height in Baffin Bay also shoaled the gradient between the Arctic Ocean and Baffin Bay, reducing the inflow of cold Arctic Water through the CAA. The changes in the southward transport through the CAA and the stronger stratification in Baffin Bay reduced the lateral and vertical heat fluxes, causing warmer subsurface waters in Baffin Bay (i.e., warming of the WGIW). Warmer WGIW on the eastern shelf and being higher in the water column could consequently contribute to accelerate the melt of Greenland glaciers. The rapid mass losses of the Greenland ice sheet in the recent decade [*Holland et al.*, 2008; *Lewis and Smith*, 2009; *Loyd et al.*, 2011; *Straneo and Heimbach*, 2013] are partly attributed to the accelerated basal melt of marine-terminating glaciers [*Joughin et al.*, 2008; *Johannessen et al.*, 2011; *Straneo and Heimbach*, 2013], which in western Greenland is correlated with warmer subsurface waters entering the fjords [*Holland et al.*, 2008; *Motyka et al.*, 2011; *Straneo and Heimbach*, 2013; *Myers and Ribergaard*, 2013; *Gladish et al.*, 2015].

Recent warming of shelf waters in Baffin Bay is associated with an increased inflow of Irminger water across Davis Strait [*Zweng and Münchow*, 2006; *Curry et al.*, 2014]. The variability of this transport is controlled by atmospheric circulation, whereby a negative winter index of the North Atlantic Oscillation (the case between 1995 and 2005) was correlated with larger transport of Irminger Water in the WGC [*Myers et al.*, 2007]. Therefore, it is possible that atmospheric circulation changes could have triggered the initial warming and the accelerated melt of west Greenland glaciers [*Holland et al.*, 2008].

In addition, warmer shelf waters may also be linked to changes in circulation within Baffin Bay associated with a reduced Arctic water inflow [*Myers and Ribergaard*, 2013; *Gladish et al.*, 2015]. There is recent evidence suggesting a decline of Arctic water inflow into Baffin Bay between 1998 and 2011 [*Peterson et al.*, 2012], and similar changes can be interpreted from mooring data at Davis Strait, whereby a comparison of the periods 2004–2010 and 1987–1990 revealed a decline in the southward transport of Arctic water [*Curry et al.*, 2014].

In our simulations, we associate the warming of shelf waters and the WGIW with a reduction in the southward volume transport through the CAA and an increased stratification due to the accumulation of freshwater in Baffin Bay. The cold Arctic inflow through the CAA is responsible for the lateral heat losses of the WGIW, while the stratification affects the vertical heat losses between subsurface and surface water layers. The similarity in the changes in transport and a warming of the shelf waters between the observations and our experiments

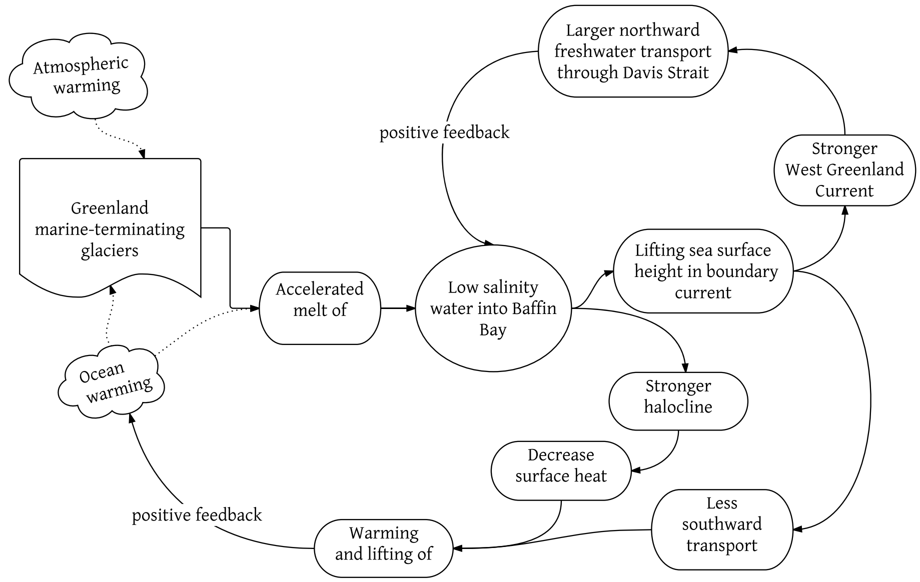

Figure 4. Schematic of findings highlighting the positive feedbacks that developed as meltwater runoff from Greenland ice sheet increases.

suggests that Baffin Bay may already be responding to the melting of marine-terminating glaciers. Therefore, we suggest that once such melting has begun, the hydrographic response of Baffin Bay is to create positive feedbacks that will continue to accelerate melting (Figure 4).

In our simulation with highest runoff, the heat content on Greenland's northwest shelf increased by 80 EJ, and the WGIW warmed by 0.6°C. The WGIW also shoaled to depths of up to 50 m in some areas along the northwest Greenland shelf. Under this setting, the WGIW can more easily spread into the fjords with shallower sills and enhance basal melting of marine-terminating glaciers. We suggest that increased meltwater production could positively feedback to accelerate melting of marine-terminating glaciers (Figure 4). Further analysis with a higher-resolution/local fjord model, including studies examining the detailed response and timing of glacier response to warm water intrusions, would contribute to the understanding of the degree of scope of this feedback.

In addition, considering the impact of enhanced Greenland ice sheet melt on the Arctic Ocean and freshwater routing, we find that the reduction in the fluxes through the CAA is compensated by a higher freshwater transport through Fram Strait. The change in the freshwater routing may have implications on Labrador Sea water formation, as the fate of some of the freshwater in the east Greenland current is the Labrador Sea [*Myers*, 2005; *Myers et al.*, 2009]. The increased melt from west Greenland glaciers, on the other hand, may not be evident in the Labrador Current or further south as it is being stored in the upper layers of Baffin Bay. One would expect, however, that these waters will be released from Baffin Bay eventually.

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