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Distinct Ocean Responses to Greenland's Liquid Runoff and Iceberg Melt

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Key Points:

- Greenland solid discharge is parameterized either as liquid runoff from the coast or explicitly represented by an iceberg model
- Icebergs act as freshwater reservoirs that affect how much, when, and where freshwater is delivered to the ocean
- Differences between the two simulations (all-liquid run versus iceberg run) are usually within their internal variability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

While Greenland discharge has been increasing in the last decades, its impact on the Meridional Overturning Circulation (MOC) is not clearly established. Because of that, the accuracy of this discharge representation in ocean models has not been a priority in large-scale circulation studies. Many models prescribe Greenland discharge solely as liquid runoff from the coast—even though around half of this mass loss is attributed to solid discharge. In this study, we use sensitivity experiments carried out with the Nucleus for European Modeling of the Ocean general circulation model to show the most relevant impacts that different Greenland solid discharge parameterizations (transforming it to liquid runoff or explicitly representing it through an iceberg model) have on the western subpolar Atlantic. We find that icebergs act as freshwater reservoirs that affect *how much*, *when*, and *where* freshwater is delivered to the ocean. They carry large amounts of freshwater away from boundary currents, releasing it in the interior of the subpolar gyre. Moreover, the amount and variability of freshwater delivered to the ocean depend not only on the characteristics of Greenland discharge itself but also on the environmental conditions icebergs are subjected to. We also find a large difference in subsurface temperatures in the Gulf of Saint Lawrence, which suggests that different Greenland discharge parameterizations might have far reaching implications beyond the MOC. Although differences in ocean fields between the simulations are usually small and within their interannual variability, they might be relevant as Greenland calving rates increase with global warming.

Plain Language Summary

The Greenland Ice Sheet is one of the main contributors to sea level rise since it has been discharging an increasing amount of water (melt) and ice (icebergs) to the ocean in the last decades. Scientists that use numerical models to study the ocean circulation and climate often represent Greenland's discharge solely in liquid form (melt) when, in reality, about half of it happens in the solid form (icebergs). In this study, we investigate how this approach—assuming all of Greenland's discharge as liquid water—differs from representing the solid discharge as icebergs in terms of effects on the ocean physical properties. Results show that, while most ocean responses between the two approaches are only slightly different, icebergs change how much, where, and where melt water enters the ocean. We also show that this distinct delivery of melt water can affect the ocean circulation, which might have consequences for ecosystems that depend on it.

1. Introduction

The annual mass loss (hereafter referred as discharge) from the Greenland Ice Sheet (GrIS) is currently estimated to be around 1,100 Gt/yr, half of which is attributed to liquid runoff and the other half to solid discharge (Bamber et al., 2012, 2018; van den Broeke et al., 2009). While liquid runoff includes surface runoff and subglacial discharge, solid discharge is a product of the ice velocity and the glacier flux gate, located around the glacier's grounding line (Figure 1a; Bamber et al., 2018). Although other frontal ablation processes (such as submarine melting) are also responsible for transforming Greenland's solid discharge into liquid freshwater delivered to the ocean, most of this solid discharge can be attributed to the formation of icebergs (i.e., calving). Between 10% and 50% of those icebergs melt in the fjord (Enderlin et al., 2016), and the remaining drifts into open ocean. Because Greenland is situated close to areas of dense water formation such as the Labrador Sea, it follows that its freshwater discharge could reduce surface water salinities and thus increase water column stability to the point where deep convection is reduced or halted, disturbing the Meridional Overturning Circulation (MOC). However, despite the fact that this discharge from Greenland has been increasing over the last 20 years (Bamber et al., 2018), such enhanced freshwater has not impacted the MOC yet (Böning et al., 2016) since most of it does not directly reach the convective region of the Labrador Sea (Böning et al., 2016; Gillard et al., 2016; Luo et al., 2016;

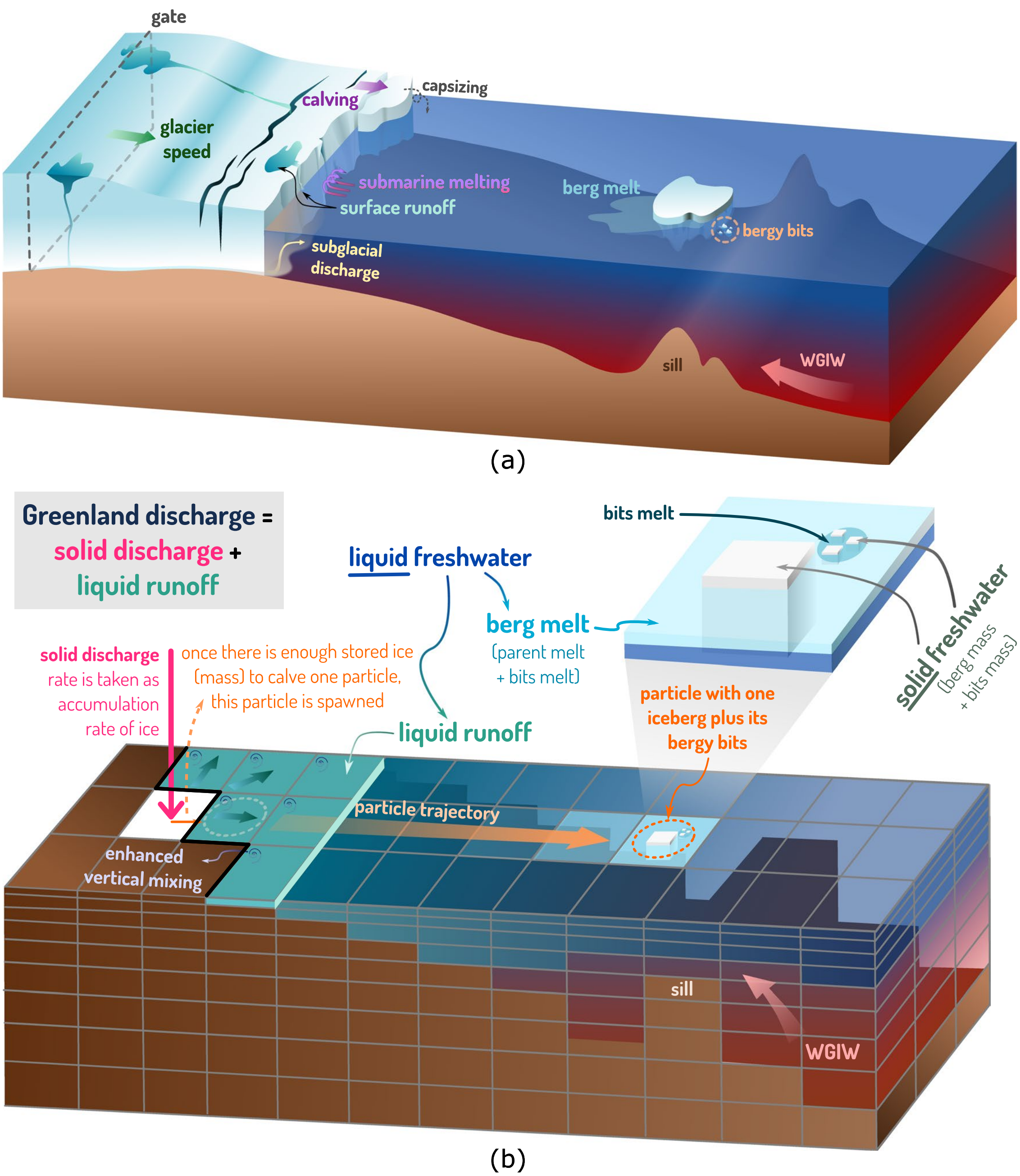

Figure 1. Schematics showing processes that deliver freshwater from land ice to the ocean (a) The real world and (b) As parameterized in the model. The several terms used in the text to describe different freshwater components are also defined in (b).

Marsh et al., 2010). Moreover, its importance to convection is much reduced when compared to the interannual variability of atmospheric forcing and associated ocean heat loss (Garcia-Quintana et al., 2019). For this reason, Greenland discharge prescription has not been a primary concern in large-scale ocean model studies, and the explicit representation of solid discharge as icebergs is often ignored due to the additional computation demand.

Even if its impact on the MOC has been imperceptible, accelerating Greenland discharge is likely altering the physical conditions of the North Atlantic. Stammer (2008) showed that, when Greenland liquid runoff was increased in a 1°-resolution simulation, a series of anomalies in surface and subsurface temperature and salinity arose due to stronger stratification. Moreover, those anomalies propagated to other basins through Kelvin and Rossby waves over a decade. Marsh et al. (2010) used a higher resolution simulation (1/4°) to show that freshwater remains mainly within boundary currents and, after 8 years, accumulates in Baffin Bay and changes its circulation. Castro de la Guardia et al. (2015) studied the impact of enhanced Greenland discharge in Baffin Bay and showed a warming of subsurface waters in that region. Those studies, however, have prescribed Greenland discharge only in liquid form, either from the coast or as a homogeneous surface flux over a large area ("hosing" experiments). This can lead to errors in the ultimate freshwater destination, especially in high-resolution models (Weijer et al., 2012), since icebergs have different pathways compared to liquid discharge, carrying freshwater away from the coast (e.g., Marson et al., 2018; Martin & Adcroft, 2010).

There have been studies that have included iceberg representation when evaluating the impacts of Greenland discharge to the surrounding ocean. Bügelmayer et al. (2015) compared the effects of using explicit iceberg representation with releasing the corresponding freshwater as liquid from the coast and noticed an increase in sea ice thickness, especially in Baffin Bay, mostly due to iceberg take up of latent heat from the ocean. They pointed out that if a local latent heat flux is also prescribed with the liquid Greenland discharge, the differences with the iceberg simulation are very small. However, the model used in their study had a coarse resolution (3°) and therefore does not capture the important role of narrow boundary currents and mesoscale eddies in transporting most of the freshwater (Marsh et al., 2010). This means that the pathway of freshwater in a coarse resolution model can be much more spread out, resulting in a similar distribution pattern when compared to the explicit representation of icebergs. In Marsh et al. (2015), the resolution was increased to 1/4° but the focus was the impact of solid versus liquid discharge in the Southern Ocean. Differently from North Atlantic studies, they found a decrease in both the sea ice concentration and thickness around most of Antarctica. It is important to note that the iceberg model used by Marsh et al. (2015) lacks a heat flux parameterization, which Jongma et al. (2009, 2013) and Bügelmayer et al. (2015) pointed out as having an important impact on the ocean—in some cases, more important than the freshwater contribution from icebergs. Moreover, none of those studies took into consideration ocean subsurface temperatures and velocities when forcing the icebergs' thermodynamic equations, which can lead to different freshwater distribution patterns (Marson et al., 2018).

Here we evaluate the ocean impacts of prescribing Greenland discharge as liquid in its entirety or dividing it into liquid and solid components, the latter being explicitly represented by icebergs. We use two sensitivity experiments to verify the most important changes in the physical ocean fields of the western subpolar North Atlantic (mainly Baffin Bay and Labrador Sea interior). This region was specifically chosen since it represents the main destination for Greenland's discharge, both in liquid (Gillard et al., 2016) and solid (Marson et al., 2018) forms.

2. Model and Experiments

Our two sensitivity experiments were carried out with the Nucleus for European Modeling of the Ocean (NEMO v3.4; Madec & the NEMO team, 2008), a model that couples ocean and sea ice (Louvain-la-Neuve Sea Ice Model 2; Bouillon et al., 2009; Fichefet & Morales Maqueda, 1997). The reader should refer to Dukhovskoy et al. (2016) for additional configuration setup and parameter details. The domain covers the Arctic and Northern Hemisphere Atlantic (the ANHA configuration), with open boundaries at 20°S in the Atlantic Ocean and at the Bering Strait, horizontal resolution of 1/4° (ANHA4), and 50 vertical levels. We use GLORYS2v3 (Masina et al., 2015) for boundary and initial conditions and the Canadian Meteorological Center's global deterministic prediction system reforecasts (CGRF; Smith et al., 2014) for atmospheric forcing. CGRF has hourly fields from 2002 to 2016 (the period for which the simulations were run, with 5-day average outputs) at a spatial resolution of 33 km. Monthly Greenland discharge was provided by Bamber et al. (2012) on a 5×5 km grid and was remapped to the ANHA4 grid. According to the averages estimated in Bamber et al. (2012), we divided the total discharge into 46% liquid runoff and 54% solid discharge. Liquid runoff is released from Greenland's coast into a number of neighboring grid points at the surface with increased vertical mixing (from the background value of 1×10^{-5} to 2×10^{-3} m^2/s) in the upper 30 m (Figure 1b). The way that solid discharge was prescribed depended on the experiment. In LIQ, we transform solid discharge into liquid runoff, so all Greenland discharge is released to the ocean in liquid form from the coast. In the second experiment, called ICB, we prescribe the solid fraction (54%) by explicitly representing icebergs.

The iceberg module in NEMO is based on Bigg et al. (1996, 1997) and was improved and adapted by Gladstone et al. (2001), Martin and Adcroft (2010), Marsh et al. (2015), and Merino et al. (2016). The solid discharge rates provided to the model enter as accumulation rates, which are subdivided into 10 different iceberg size categories

Table 1
Simulations Used in This Study

Simulation	Model	Greenland discharge	Liquid	Solid	ICB heat flux
LIQ	NEMO v3.4	Bamber et al. (2012)	100%	–	–
ICB	NEMO v3.4	Bamber et al. (2012)	46%	54%	Yes
$ICB_{no\ heat\ flux}$	NEMO v3.4	Bamber et al. (2012)	46%	54%	No
ICB_{tracer}	NEMO v3.6	Bamber et al. (2018)	42%	58%	Yes

Note. "Liquid" and "solid" refer to the fraction of the total Greenland discharge that was prescribed as liquid and solid (iceberg) discharge.

according to a statistical distribution (which can be seen in the "Calving distribution" column from Table 1 in Martin and Adcroft (2010)). Once there is enough mass to calve a particle (a group of icebergs) of a given size category, this particle is spawned into the model (Figure 1b). The number of icebergs included in each particle varies with its size category (for details, see Martin & Adcroft, 2010). Those Lagrangian particles will drift as a function of the pressure gradient force; the Coriolis force; the wave radiation force; and drag forces from atmosphere, sea ice and ocean. In the latter, the ocean velocity is obtained by averaging the velocities from surface to iceberg keel (a scheme we refer to as "vertically integrated"; Marson et al., 2018). As they travel, icebergs deteriorate due to wave erosion, bottom and side melting, which is dependent on the averaged ocean temperature along the iceberg draft (again, a feature of the vertically integrated scheme). Here, the iceberg mass lost due to wave erosion is divided into 70% liquid melt and 30% bergy bits (smaller pieces of ice that break off the parent iceberg and travel with it; see Figure 1). The generation of bergy bits was introduced in the model by Martin and Adcroft (2010) and the fraction of mass we use to produce them comes from a rough estimate based on the very few existing observations, presented by Savage (2001). For more details on the iceberg model, please refer to Merino et al. (2016) and Marson et al. (2018).

Marsh et al. (2015) noticed that the northern hemisphere iceberg mass takes around 15 years to reach equilibrium. To avoid this long "iceberg spin-up," we used final *iceberg fields* from a previous 15-year simulation as the initial iceberg fields in ICB (all the other initial conditions were *not* taken from this 15-year simulation, but from GLORYS2v3). The iceberg model passes both meltwater and latent heat fluxes to the ocean component's first level (surface). Since the solid discharge is taken as a fraction of the total discharge, it retains the seasonal cycle characteristic of the liquid runoff. Although calving is not considered to have a marked seasonality because it depends on the slow progression of the glacier front, the release of icebergs peaking during late spring to summer is realistic if we think of this as the time the ice mélange is less dense (e.g., Howat et al., 2010) and allows icebergs to escape the fjords, which are not resolved at 1/4° resolution.

Two additional simulations will be mentioned in this article. One of them is a twin of ICB but with no flux of latent heat between iceberg and ocean; we call this run $ICB_{no\ heat\ flux}$. The fourth simulation (ICB_{tracer}) was configured similarly to ICB—except for NEMO's version, which is 3.6, and the Greenland discharge forcing, which was updated to the Bamber et al. (2018) product. The differences between Bamber et al. (2012, 2018) products are detailed in Gillard (2020), but for our purposes it suffices to know that, in Bamber et al. (2018), liquid runoff represents 58% of the total Greenland discharged mass between 1959 and 2016, while the remaining 42% can be attributed to solid discharge (versus the 46% and 54% ratios we mentioned for Bamber et al., 2012). See Table 1 for a summary of the main differences among the simulations used.

We will use the simulations' results from the third model year (2004) onwards unless specified otherwise, since the model takes about 2 years (2002–2003) to adjust to the forcing fields. When LIQ and ICB are compared as time series for a specific region, we averaged the corresponding area enclosed by the contour in Figure 2 and plot the 5-day averaged output. The time series also show the differences between ICB and LIQ with respect to LIQ standard deviation, so those differences can be seen in the perspective of the system's inherent variability. Freshwater content and transport were calculated using a reference salinity of 34.8, which is the mean Arctic Ocean salinity (Aagaard & Carmack, 1989). The transects through which transports were calculated are also indicated in Figure 2.

In order to estimate subduction rates in the Labrador Sea, we used a kinematic approach described in detail by Costa et al. (2005) and Courtois et al. (2020). Briefly, the subduction rate for a given year and density range results from the sum of the fluxes across the mixed layer base due to (a) its depth variation $\frac{\partial H}{\partial t}$, (b) the advection occurring horizontally across the mixed layer sloped base $\mathbf{v}_h . \nabla H$, and (c) the vertical velocity at its base w_b, integrated over that year and density range. Mathematically,

$$S(\sigma) = \frac{-1}{t} \int_0^{\tau} \int_{A_\sigma} \left[w_b + \frac{\partial H}{\partial t} + \mathbf{v}_h \cdot \nabla H \right] dA_\sigma dt \qquad (1)$$

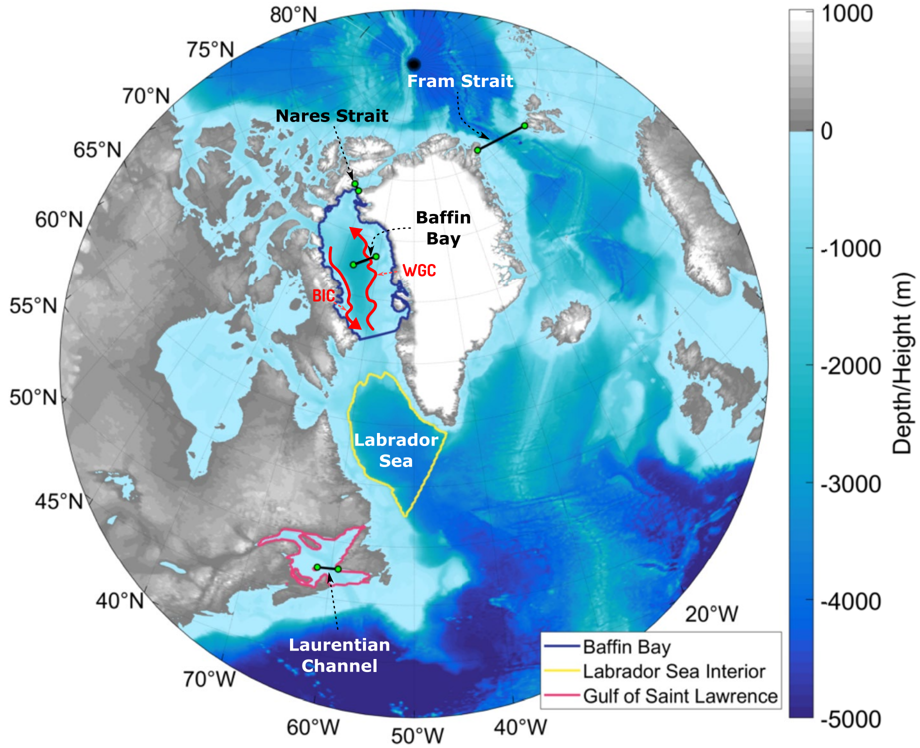

Figure 2. Map showing the regions where averages were made to produce time series: Baffin Bay, Labrador Sea Interior (deeper than 1,000 m), and Gulf of Saint Lawrence. The sections used to calculate transport are indicated by the black lines ending with green circles. Red arrows indicate the near-surface cyclonic circulation of Baffin Bay, comprised by the West Greenland Current (WGC) and the Baffin Island Current (BIC).

where $S(\sigma)$ is the yearly ($\tau = 1$ year) subduction rate at a density range $\sigma + \delta\sigma$ and A_σ represents the surface area outcrop of the isopycnals of $\sigma + \delta\sigma$.

3. Results and Discussion

First, we compare the averaged annual cycle of freshwater mass entering the ocean from Greenland among different components (Figure 3a) and different simulations (Figures 3b and 3c). The mass of Greenland icebergs in the ocean (berg mass) stabilizes once it reaches ∼200 Gt, which agrees with the Marsh et al. (2015) estimate, who noticed that this mass is reached after 15 years of simulation. That is why we initialized the ICB run with a stable iceberg field. The calved mass (green line in Figure 3a) increases the mass of icebergs in the ocean. When those icebergs deteriorate, they either produce liquid melt (berg melt, purple line in Figure 3a) or bergy bits (pink line, which, once melted, will add to the iceberg melt as well). The peaks of iceberg melt and bergy bits production lag the calving peak by one and two months, respectively. This agrees with the mode of the icebergs' lifetime calculated from the model output, which is 25 days (see complete lifetime distribution in Figure S1). Total Greenland discharge is shown by the blue circles; these include solid and liquid discharged mass. By comparing the orange line and blue circles in Figure 3a, we see that, on average, the accumulated mass of icebergs in the ocean surpasses the total GrIS discharge.

In Figures 3b and 3c, we compare the amount of *liquid* freshwater entering the ocean in the two simulations, both as runoff from the coast or as iceberg melt. While LIQ (blue line) is simply the total Greenland discharge (as the blue circles in Figure 3a), ICB (orange line) is 46% of the total discharge (attributed to liquid runoff) plus the iceberg (and bits) *melt* (Figure 1b). Figure 3b shows that the whole annual cycle of delivered freshwater mass in ICB is delayed by 1–2 months with respect to LIQ, which makes sense given the average lag between calving and melting previously mentioned. A fair amount of freshwater mass that is "missing" from the spring rise and summer peak in ICB is distributed throughout autumn, making the ICB curve more broad than the LIQ one. Even with this seasonal redistribution of freshwater mass delivery, and although the prescribed mass discharged from

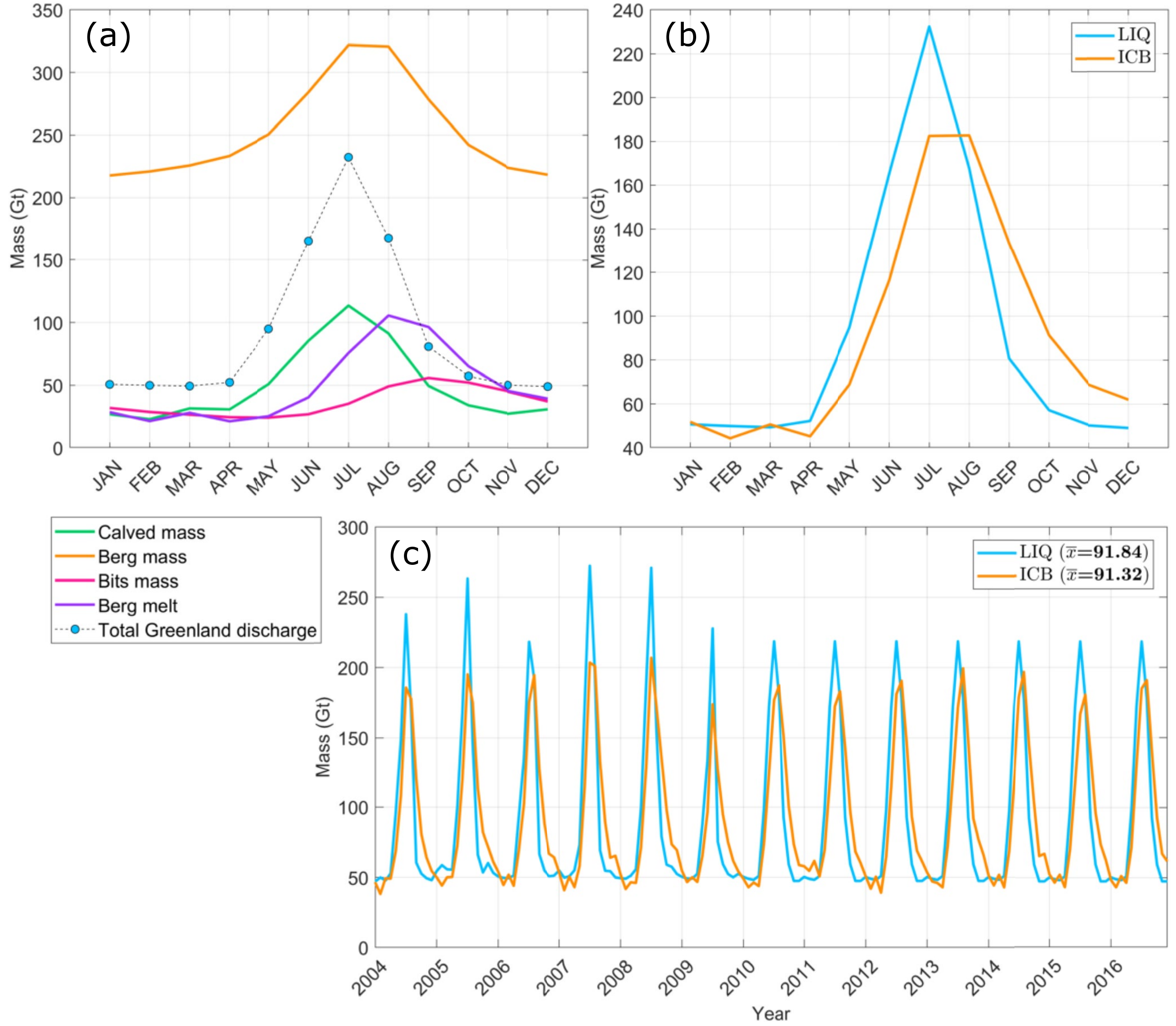

Figure 3. (a) Mean annual cycle of mass of freshwater in or entering the ocean from the ICB simulation, divided into the different terms that release or store it: monthly averaged calved mass (green line), monthly averaged iceberg mass present in the ocean (orange line), monthly averaged bergy bits mass present in the ocean (pink line), monthly melted mass from all icebergs (purple line). The blue circles show the total (100%) Greenland mass discharge (solid plus liquid components) averaged by month. (b) Mean annual cycle of *liquid* freshwater entering the ocean. The blue line (LIQ) is the same as the blue circles in (a), since all Greenland discharge is prescribed as liquid runoff in LIQ. The orange line (ICB) shows 46% of the total Greenland discharge (attributed to Greenland's liquid runoff) plus iceberg melt. (c) Same as (b), but expanded into a time series to show interannual variability.

Greenland for LIQ and ICB is the same, the iceberg run has effectively less liquid freshwater entering the ocean. The difference between LIQ and ICB total liquid mass entering the ocean between 2004 and 2016 (Figure 3c) is around 22 Gt. This occurs because, as mentioned before, iceberg melt lags calving in the model—usually by months, but sometimes by years (Bigg et al., 1997; Marson et al., 2018). Therefore, part of the calved mass remains in solid form through the end of each melting season. This allows icebergs to act as a freshwater reservoir that "buffers" the liquid freshwater delivery to the ocean: the variability of liquid freshwater entering the ocean in LIQ is larger than in ICB (61.69 Gt versus 49.89 Gt, Figure 3c). As a result, in years where liquid runoff is relatively low, the ICB run might have a comparatively large liquid freshwater input regardless of that year's discharge rates. See, for example, the summer of 2013 compared to summer of 2007 (Figure 3c), where the liquid freshwater mass released in ICB is about the same, while in LIQ its peak is about 50 Gt smaller.

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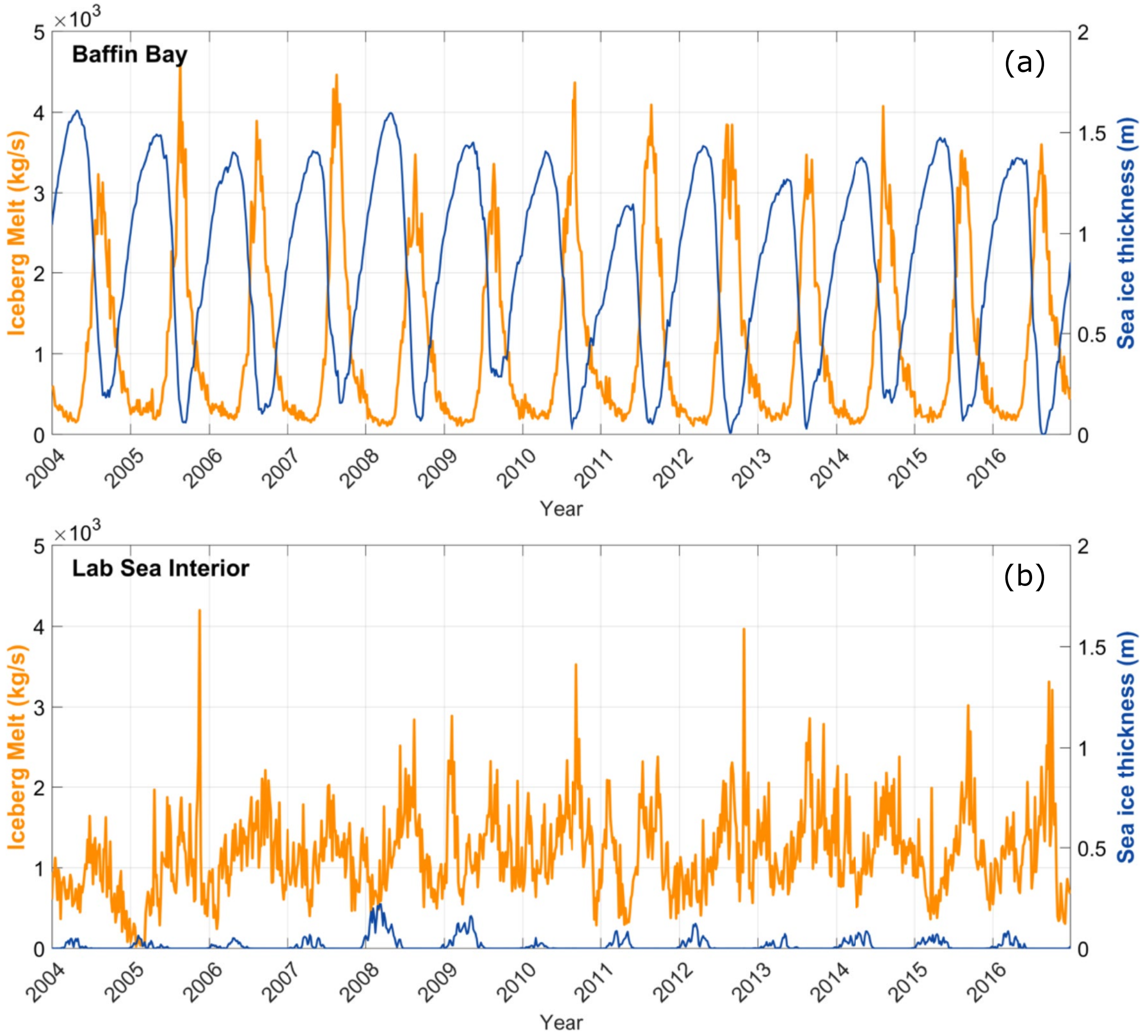

Figure 4. Iceberg melt rate (orange) and sea ice thickness (blue) in ICB, averaged for (a) Baffin Bay and (b) The Labrador Sea interior.

Another interesting difference between ICB and LIQ regarding liquid freshwater delivery timing can be seen in the iceberg melt variability for different regions (Figure 4). While in Baffin Bay the icebergs melt with a marked seasonality that has a maximum between mid-August and early September and a minimum between mid-March and early May, the icebergs in the Labrador Sea interior melt with a more random variability. The marked seasonality in iceberg melt was also observed on the west Greenland shelf and on the Labrador Sea shelf, while random variability was seen on the north Greenland shelf and the over entire subpolar gyre (which includes the Labrador Sea interior; Figure S2). The different patterns of iceberg melt are likely associated (negatively correlated) with the presence or absence of sea ice, which peaks around March (maximum) and September (minimum, Figure 4a). In regions seasonally covered by sea ice, icebergs will melt at greatly reduced rates when sea ice thickness reaches its maximum. This happens because iceberg melt is mostly attributed to wave erosion (Marsh et al., 2015), which is primarily a function of the surface temperature that remains at freezing point when sea ice is present. Melt at this time, then, is restricted to the deeper layers reached by the iceberg draft. In ice-free or permanently ice-covered areas, the melt will respond only to an ocean whose temperature variability is unconstrained by the sea ice freezing/melting cycle and, to a second degree, to atmospheric forcing when sea ice is absent.

The fact that icebergs hold part of the Greenland discharged freshwater in solid form for months and are able to export this freshwater far away from their calving point, makes the ICB upper layers (0–50 m) slightly saltier (by 0.08, on average, between 2004 and 2016) than in LIQ in Baffin Bay (Figure 5a). ICB is also slightly colder (by −0.12°C, on average, between 2004 and 2016) in the 0–50 m layer than LIQ in Baffin Bay (Figure 5b), since

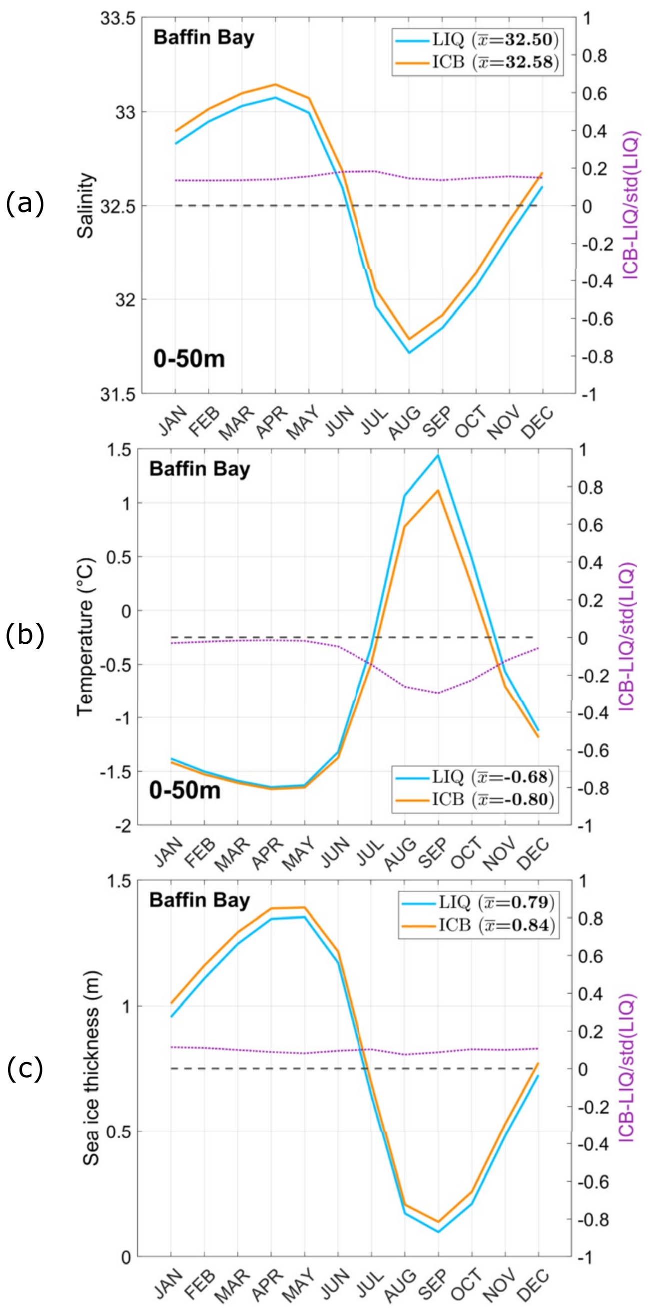

Figure 5. Baffin Bay's mean annual cycle of (a) Salinity at 0–50 m; (b) Temperature at 0–50 m; and (c) Sea ice thickness. The blue (orange) line shows LIQ (ICB) mean annual cycle, and the dotted purple line shows the mean annual cycle of their difference with respect to LIQ's variability. The numbers indicated by $\bar{x}$ are the corresponding simulation's time average for the variable and basin in question.

icebergs take up latent heat from the ocean in order to melt. This leads to a slightly increased sea ice thickness (by 5 cm, on average, between 2004 and 2016) in this region (Figure 5c). There is very little interannual variability in those differences throughout the simulation in these upper layers, which is why we are presenting their mean annual cycle. The situation changes when deeper layers are considered. Figure 6a shows the time series of freshwater content in Baffin Bay which is, indeed, larger in LIQ from 2004 to 2010. However, the difference between ICB and LIQ (purple dotted line) starts to decrease in mid-2008 and reverses by the end of 2010, when it oscillates between positive and negative values. This freshwater content difference mostly reflects salinity differences at 100–500 m (Figure 6b) instead of those detected close to the surface (Figure 5a). To understand what is happening with the salinity field at 100–500 m (and, consequently, the freshwater content), we need to bring Baffin Bay's circulation into the picture.

Figure 2 shows the two main currents (in red arrows) that comprise Baffin Bay's cyclonic circulation: the northward West Greenland Current (WGC) along Greenland's shelf break and the southward Baffin Island Current along the Baffin Island shelf break. Because there is more freshwater close to the surface over Greenland's shelf in LIQ (Figure 7c; Figures S2 and S3), the steric height in this region is larger than in ICB, which means that LIQ has a sharper surface pressure gradient between Greenland shelf and the center of Baffin Bay (Figure 7a). This generally results in an intensified WGC in LIQ compared to ICB, which can be seen as the blue area over the shelf-break in the cross-section velocity anomaly panel (Figure 7d). Associated with this intensified WGC, more West Greenland Irminger Water (WGIW) is brought into Baffin Bay. This water mass is characterized by temperatures equal to or higher than 2 °C and salinities equal to or higher than 34.1 (Curry et al., 2014) and it is indicated by the black contours in Figures 7b and 7c using this definition (solid contour for LIQ, dashed for ICB). Notice how this water mass expands offshorewards in LIQ and also has a slightly warmer and saltier core compared to ICB. If we look back at Figures 6b and 6c, we can now understand what is happening with salinity and temperature in Baffin Bay between 100 and 500 m. The subsurface salinity differences between ICB and LIQ are not only controlled by the amount of freshwater being released near the surface (that eventually mixes downward as the mixed layer deepens during winter) in each of the simulations, but also to the fluctuating volume of WGIW (relatively salty) entering Baffin Bay (see Figure S5a). Subsurface temperatures remain colder in ICB throughout the entire simulation. In the first years, this might be attributed to the latent heat flux associated with iceberg melt and increased cold Arctic water export through Nares Strait in ICB (further discussed below). After 2008, however, the temperature difference between ICB and LIQ increases and it is associated with the enhanced presence of warmer WGIW in Baffin Bay in LIQ.

This mechanism of "more freshwater, steeper sea surface height (SSH) gradient, intensified WGC, more WGIW in Baffin Bay" was discussed in Castro Castro de la Guardia et al. (2015) when comparing two simulations with different Greenland discharge magnitudes. One interesting feature that those authors did not point out is that, although the WGC is indeed intensified when there is more freshwater coming off Greenland, the northward transport through the whole water column is not always larger (Figure S5b). Figure 7d indicates why that happens: larger speeds are observed in the deeper layers in ICB relative to LIQ (notice the yellow area delineated by the solid black contour). In fact, the uniformity of velocities between 500 m and the bottom observed in ICB (Figure 7e) indicates a more barotropic circulation

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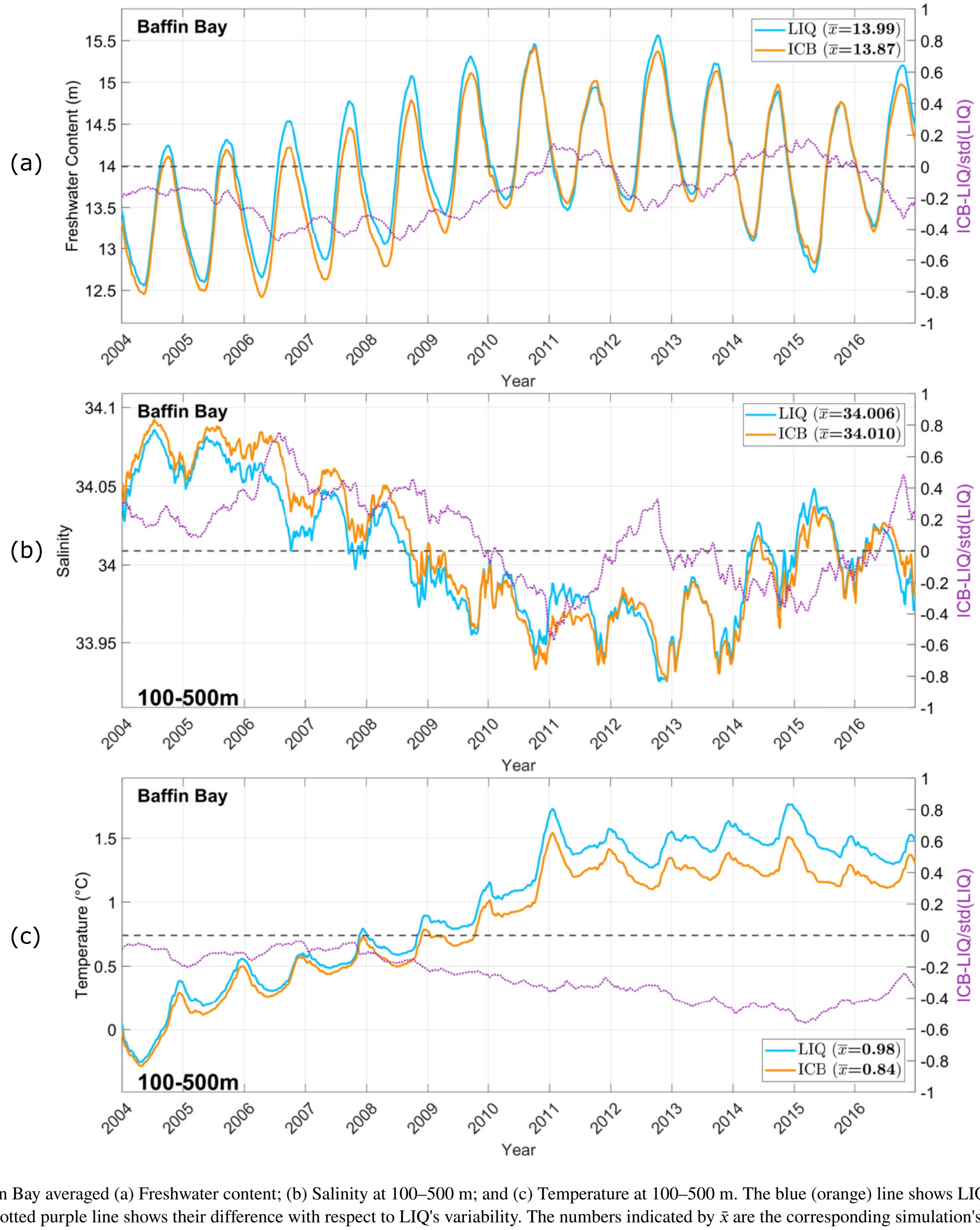

Figure 6. Baffin Bay averaged (a) Freshwater content; (b) Salinity at 100–500 m; and (c) Temperature at 100–500 m. The blue (orange) line shows LIQ (ICB) time series, and the dotted purple line shows their difference with respect to LIQ's variability. The numbers indicated by $\bar{x}$ are the corresponding simulation's time average for the variable in question.

compared to LIQ. This is likely a result of the slightly weaker stratification brought by less surface freshwater input in ICB, which allows momentum to be transferred more efficiently downward.

Now we are left with this question: if icebergs are carrying freshwater away from the Greenland shelf (Figure S3) and Baffin Bay (Figures 5a and 6a), where is this freshwater being released to the ocean? To help answering this question, we analyzed the final destination of iceberg melt versus liquid runoff using passive tracers. This was done using an additional simulation (ICB_{tracer}) that contained such tracers. When we subtract the final (December

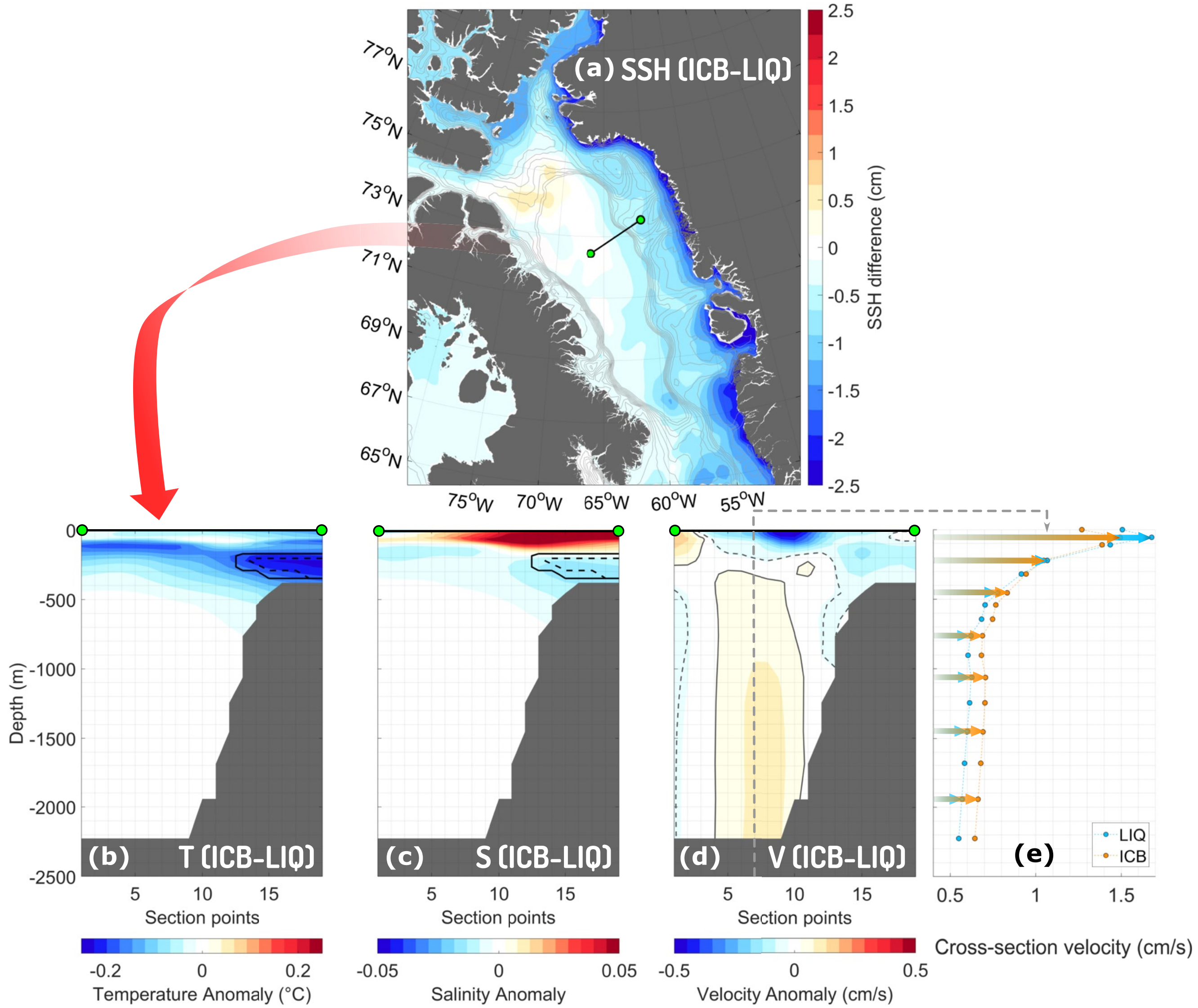

Figure 7. (a) Baffin Bay sea surface height difference between ICB and LIQ (2004–2016 average, colors). Gray lines indicate bathymetry from 100 to 1,000 m at 100 m-intervals. The black line and green circles show the position of the section depicted in (b–d). (b) Temperature and (c) Salinity difference between ICB and LIQ (2004–2016 average). The black solid (dashed) contour indicates the position of the WGIW ($T \geq 2$ °C and $S \geq 34.1$) in LIQ (ICB). (d) Cross-section velocity difference between ICB and LIQ (2004–2016 average). It is worth noting that all the averaged velocities in both ICB and LIQ are positive (northward); therefore, the sign in (d) simply indicates the anomaly, not velocity direction. Solid (dashed) contours delineate regions where currents in ICB are faster (slower) than in LIQ. (e) Cross-section velocity at section point 7 for LIQ (blue) and ICB (orange).

31, 2016) liquid runoff tracer field from the final iceberg melt tracer field, we obtain Figure 8a. As can be seen, the liquid runoff tracer concentration is larger than the iceberg melt tracer concentration everywhere since (a) there is more liquid discharge than solid (58%:42% ratio mentioned in Section 2) and (b) icebergs still hold some of the freshwater in solid form by the end of the simulation. In order to truly differentiate the areas where each tracer accumulates, then, we have "normalized" the tracers by dividing each grid cell value by the respective tracer average for the whole domain. The difference between such normalized tracer fields (Figure 8b) shows a clear distinction of freshwater destination when considering liquid or solid discharges. While icebergs also release a significant amount of freshwater in Baffin Bay and the boundary currents, those locations are still dominated by liquid runoff (blue areas in Figure 8b; Gillard et al., 2016; Luo et al., 2016; Marsh et al., 2010). The interior of the subpolar gyre, however, receives a relatively larger amount of iceberg melt (orange area in Figure 8b).

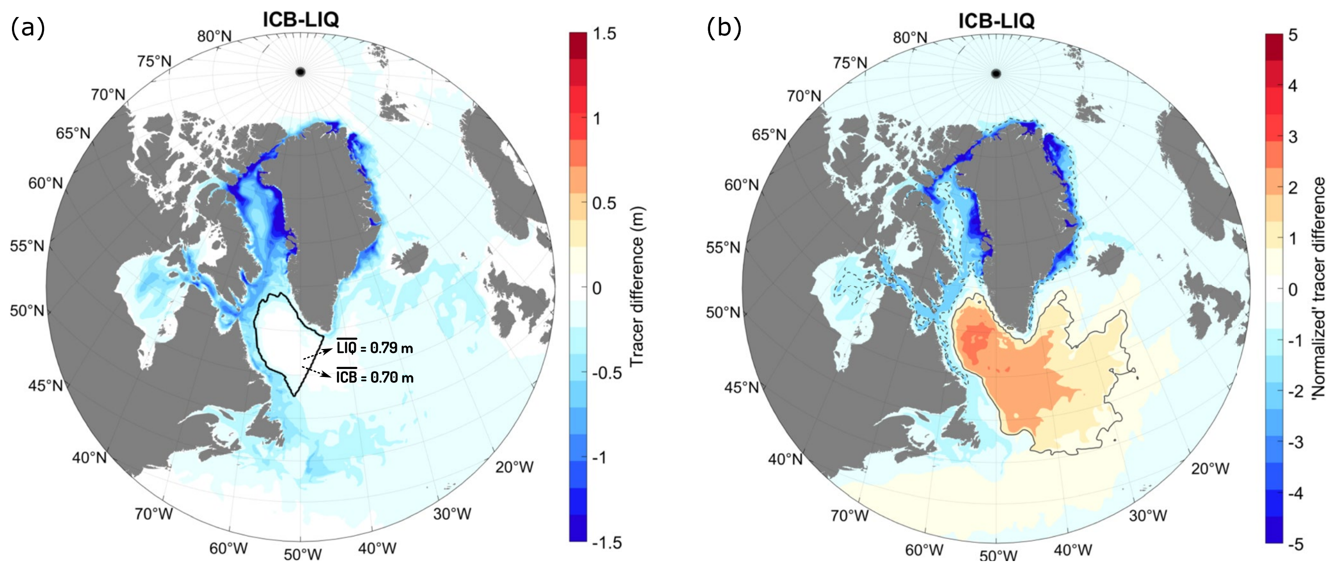

Figure 8. (a) Iceberg melt tracer minus liquid runoff tracer on the last day of simulation (December 31, 2016). The black contour shows the Labrador Sea interior mask, and numbers indicate the spatial average thickness of each tracer. (b) Same as (a), but tracers were normalized by dividing each grid cell value to the tracer's spatial average before subtracting them. Solid (dashed) lines indicate 1 (−1) isopleths to highlight the most visible positive (negative) differences in the map.

Since icebergs are more likely to bring Greenland's freshwater to the interior of the Labrador Sea, we immediately wonder how distinct ways of parameterizing Greenland discharges (liquid versus solid) might affect the formation of dense waters that is characteristic of this region. To investigate that, we start by calculating the area of the Labrador Sea interior (delimited by the yellow line in Figure 2) where the mixed layer depth (MLD) is equal to or exceeds 1,200 m (Figure 9a). The differences between ICB and LIQ areas are subtle most of the time, and oscillate from positive to negative almost yearly. In the most recent years of strong convection (i.e., 2014–2016), ICB presents a smaller area with deep MLD (see Figure S6 to compare the size of the 1,500 m March MLD area between ICB and LIQ) which is more consistent with observations (The Lab Sea Group, 1998)—albeit still too large and deep, a known issue with lower resolution simulations (Garcia-Quintana et al., 2019). This might be due to the fact that, at 1/4° resolution, while a significant fraction of the mesoscale eddies (responsible for delivering freshwater from shelf to basin) are not well represented across the southwestern Greenland shelf break, icebergs are able to deliver freshwater to the eastern Labrador Sea, shrinking the deep MLD area to the western side. It is interesting to note that, when icebergs are parameterized with *no heat flux* (in $ICB_{no\ heat\ flux}$), the freshwater content is overall smaller (Figure S4b) and the MLD is deeper. Although the heat take up from the ocean intuitively would allow less melting and deeper mixed layer depths, these effects are possibly overcome by reduced evaporation rates—and consequent freshwater content increase—associated with a slightly larger sea ice cover (by 3.6×10^9 m^2, on average, between 2004 and 2016) in ICB compared to LIQ (Jongma et al., 2009). In fact, Jongma et al. (2013) showed that taking the latent heat flux between iceberg and ocean into consideration results into a more effective weakening of the MOC (more similar to a hosing experiment), and attributed it to the increased sea ice cover. This might be because the averaged freshwater flux through the surface due to iceberg melt is an order of magnitude smaller than the flux due to other sources (net evaporation-precipitation, runoff, and sea ice freeze-melt cycle) seen from ICB, although their contribution to surface freshwater flux changes regionally (see lower right panel in Figure 3 in Marsh et al., 2015).

The annual subduction rate, averaged between 2004 and 2016, is shown in Figure 9b. The two simulations have a peak in subduction at 27.80 kg/m^3 and ICB has a slightly higher rate (1.65 versus 1.60 Sv for LIQ). Part of this water formed is further transformed into denser classes—more in ICB (0.79 Sv) than in LIQ (0.64 Sv). Looking into the interannual variability of subduction rates at 27.80 kg/m^3 (Figure 9c) we see that ICB's subduction rates are not consistently higher than LIQ for every year. The interannual variability in the difference between ICB and LIQ subduction rates is consistent with the variability of the freshwater content difference in the Labrador Sea interior (compare purple dotted lines in Figures 9c and 9d): when there is more freshwater in ICB, LIQ presents higher subduction rates and vice versa. The overall higher subduction rates in ICB (Figure 9b and 27.8

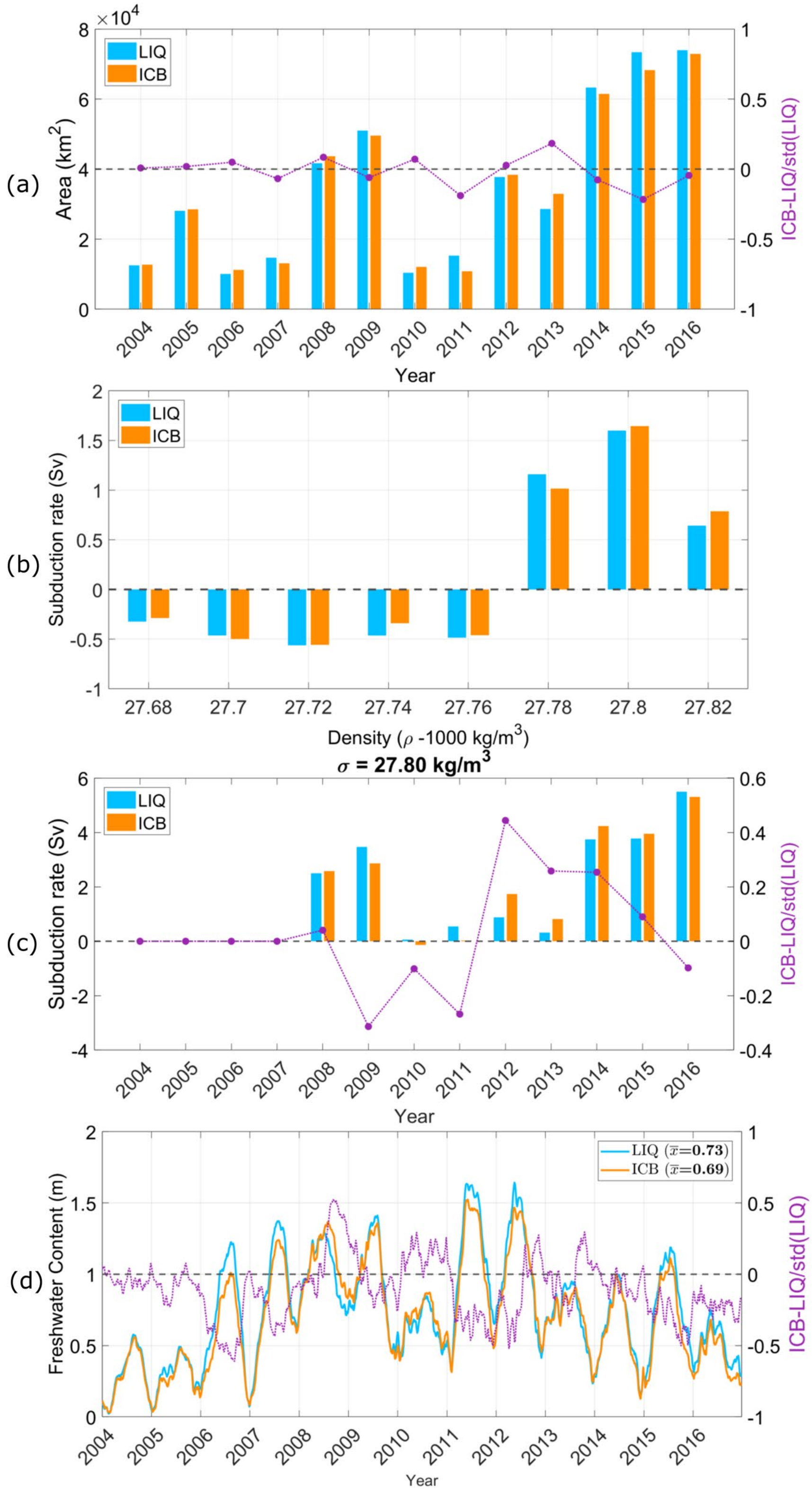

Figure 9. (a) Annually averaged area contained by the yellow line (Labrador Sea) in Figure 2 where MLD ≥1,200 m. (b) Average subduction rates between 2004 and 2016 at different density ranges. (c) Time series of subduction rate at 27.80 kg/m^3. (d) Time series of freshwater content in the Labrador Sea interior. Blue (orange) bars and lines represent values for LIQ (ICB). The dotted purple line shows ICB and LIQ differences with respect to LIQ's variability. The numbers indicated by $\bar{x}$ in (d) are the corresponding simulation's time average for the variable in question.

bin) also reflects the overall higher freshwater content in LIQ (0.73 versus 0.69 m in ICB). At first glance, the larger freshwater content in LIQ might seem in contradiction with our result that icebergs are more likely to deliver Greenland freshwater to the interior of the Labrador Sea than liquid runoff (Figure 8). However, the fact still remains that liquid runoff rates are larger than solid discharge rates, which means that there is more liquid runoff available to enter the Labrador Sea than there is iceberg melt (compare average tracer values for both simulations annotated in Figure 8a). Moreover, as seen in the map in Figure 7, the averaged SSH around Greenland in LIQ (−61.64 cm) is higher than in ICB (−62.26 cm), while Arctic averaged SSH remained the same for the two simulations at −54.75 cm. This causes the Arctic-Baffin Bay pressure gradient to be reduced in LIQ, which means LIQ has an overall smaller southward volume transport through Nares Strait (0.508 Sv) compared to ICB (0.523 Sv). This is compensated by a general increased southward volume transport in Fram Strait in LIQ (8.473 versus 8.404 Sv for ICB), a behavior previously observed by Lique et al. (2009). Since the shelf-basin freshwater exchange is much larger in the east Labrador Sea (from Greenland's shelf) than in the west (from Labrador's shelf; Myers, 2005; Pennelly et al., 2019), more freshwater coming from Fram Strait means more freshwater available to enter the Labrador Sea.

The iceberg "preference" to discharge its meltwater in the interior of the subpolar gyre is also clear in ICB_{tracer}, since the liquid:solid contributions decrease from 58%:42% at their source to 53%:47% in the Labrador Sea interior mask. The subduction rates direct response to freshwater content was expected, given that the atmospheric forcing is identical in both simulations, but their variability highlights that iceberg melt sometimes dominates the liquid runoff in this region despite the fact that the fraction of the total discharged mass is smaller for solid discharge compared to liquid. So, while iceberg melt is still reduced with respect to liquid runoff, the current increasing calving rates (e.g., Wood et al., 2018) make it possible for solid discharge to be an arguably better candidate to reduce deep convection in open ocean areas in the future.

Surprisingly, the most striking difference between ICB and LIQ was detected in the subsurface layers of the Gulf of Saint Lawrence (Figure S7 and Figure 10a). In this region, the temperatures between 100 and 500 m were higher in ICB for almost all of the studied period (with an average of 3.36°C versus 3.14°C in LIQ), and the ICB-LIQ differences reached up to twice the standard deviation of LIQ. The warming may be associated with a larger volume of Slope Water entering the Laurentian Channel in ICB, as can be seen in Figure 10b which shows the inward transport across the channel. Slope Water, which is found between the Gulf Stream and the continental shelf south of Newfoundland, is a mixture of Labrador Current water and North Atlantic Central Water (Gatien, 1976). The transport of warm waters shoreward is increased from 0.08 ± 0.07 Sv in LIQ to 0.11 ± 0.10 Sv in ICB. Indeed, when we look at an average temperature section across the Laurentian Channel (Figures 10c and 10d), we see that the warm core entering the gulf below 200 m is expanded in ICB compared to LIQ, pushing the cold and fresh outflow further up and west. For reasons we have yet to determine, runs with icebergs tend to bring an intensified Gulf Stream core closer to the coast (Figure 11), which could explain the increase of warm waters in the Gulf of Saint Lawrence.

4. Summary and Conclusions

Using two sensitivity experiments carried out with NEMO v3.4, we evaluated the distinct ocean responses to Greenland's liquid runoff and iceberg melt, emphasizing the role of icebergs as a freshwater source to the western subpolar North Atlantic. Our main findings are summarized below: points 1–4 illustrate how icebergs affect the *delivery of liquid freshwater to the ocean*, point 5 relates to the *heat flux associated with icebergs*, and point 6 indicates that Greenland's discharge parameterization might have *remote implications*. The biogeochemical impacts of icebergs are the subject of an upcoming project.

1. Icebergs act as freshwater reservoirs
   Given that the mode of the icebergs' lifetime is 25 days, nearly all calved mass in the model melts around a month later. This already sets ICB and LIQ peaks of liquid freshwater delivery to the ocean 1 month apart. Still, a small fraction of this mass remains solid by the end of each melting season. By the end of the 2004–2016 period, 22 Gt of freshwater remained in solid form in ICB, which corresponds to 0.2% of the total Greenland discharge. Therefore, slightly less liquid freshwater is delivered to the ocean in relatively short simulations (15 years or less) when icebergs represent Greenland's solid discharge compared to all-liquid discharge simulations. Moreover, the fact that the ocean is already populated with icebergs at

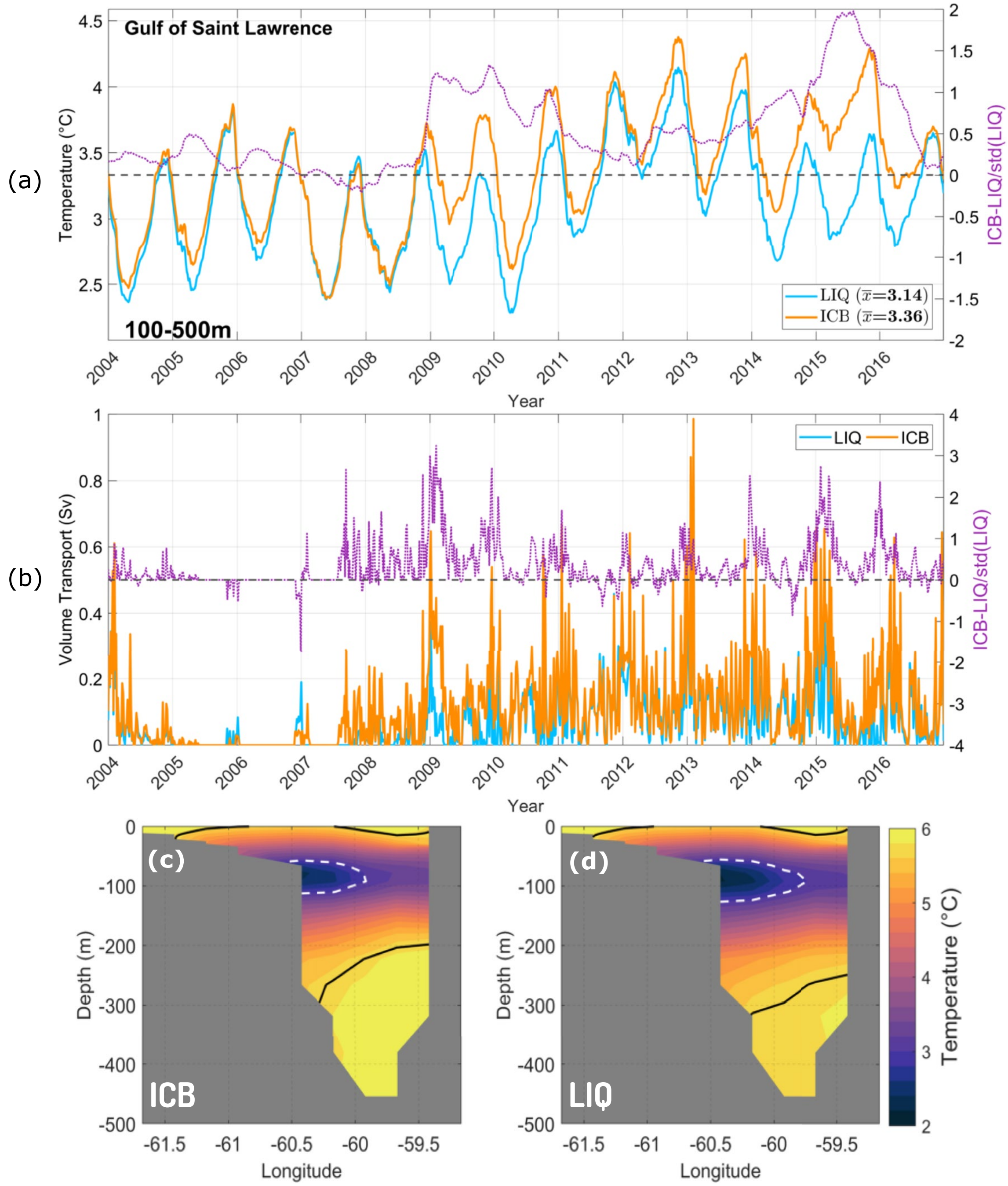

Figure 10. (a) The Gulf of Saint Lawrence's temperature averages for 100–500 m. (b) Northward transport across the Laurentian Channel. The blue (orange) line shows LIQ (ICB) time series, and the dotted purple line shows their difference with respect to LIQ's variability. The numbers indicated by $\bar{x}$ in (a) are the corresponding simulation's time average for temperature between 100 and 500 m. (c) ICB and (d) LIQ averaged (2004–2016) temperatures across the Laurentian Channel section. The solid black (dashed white) line marks the 5.7°C (3°C) isotherms to highlight the position of the warm (cold) cores.

the beginning of every model year means that icebergs "import freshwater from the previous year" in solid form and are able to release significant amounts of pure freshwater even in years when liquid runoff is reduced. That translates into a smaller interannual variability of liquid freshwater delivery in ICB compared to LIQ, meaning that icebergs act as a "buffer" in delivering Greenland's discharge to the ocean.

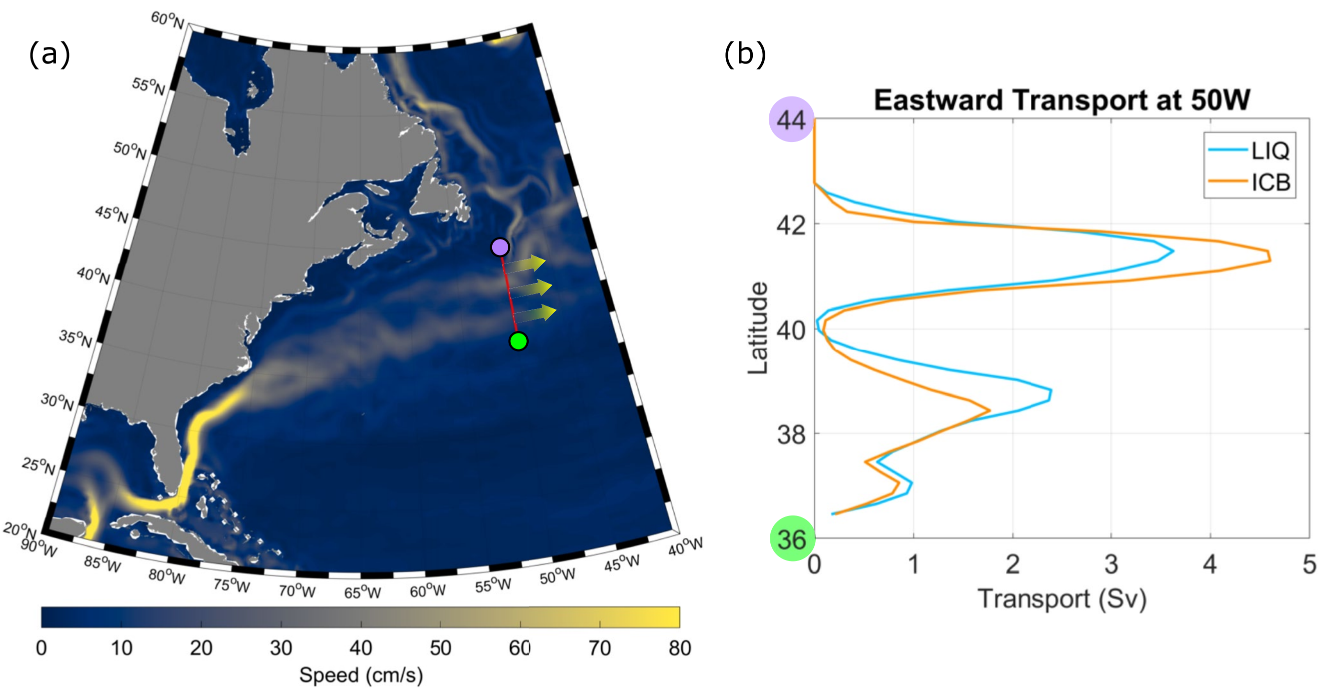

Figure 11. (a) Map showing LIQ averaged (2004–2016) speed in colors and the transect used to calculate the (b) Averaged eastward transport at 50°W (vertically integrated at each grid point along the section) associated with the Gulf Stream. Green and lavender circles were added so the reader can easily place the start and end points of the section.

2. Icebergs may alter the seasonality of freshwater delivery
   In seasonally sea ice-covered regions, iceberg melt has a marked seasonality which resembles—though with a lag—the seasonality of liquid runoff. On the other hand, iceberg melt in ice-free or permanently covered regions is more randomly variable as the ocean surface temperature is not modulated by the sea ice freezing/melting cycle.
3. Icebergs take freshwater away from their coastal origin
   Icebergs tend to redistribute freshwater offshoreward, as shown previously by Martin and Adcroft (2010) and Marsh et al. (2015). Further indirect effects of freshwater removal from the Greenland shelf and Baffin Bay in ICB compared to LIQ are:

   - An increased cold Arctic water export toward Baffin Bay through Nares Strait, since the reduced freshwater content increases the sea surface height gradient between the two basins.
   - A less intense West Greenland Current between 100 and 500 m due to the reduced sea surface height gradient between Greenland coast and the center of the bay, which also brings in less West Greenland Irminger Water—meaning that, while an increased liquid runoff discharge would create a positive feedback by bringing in more warm waters, an increased solid discharge relative to liquid runoff would weaken such feedback.
   - A more intense deep (>500 m) transport in Baffin Bay, given that ICB's slightly weaker stratification would result in a more barotropic circulation.

4. Icebergs are more likely to deliver freshwater to the interior of the subpolar gyre
   Icebergs spread freshwater differently from liquid runoff since they have different pathways. In this study, icebergs are moved with the vertically averaged (surface to iceberg keel) ocean velocities and thus will take a trajectory that coincides more with the geostrophic component of currents (Marson et al., 2018), differently from liquid runoff which is transported by surface currents. While icebergs do not reach certain regions that liquid runoff does, such as the Canadian Arctic Archipelago, they are more likely to deliver freshwater to the interior of the subpolar gyre (Figure 8b) while liquid runoff tends to concentrate along the boundary currents, which is supported by Marsh et al. (2010) and Gillard et al. (2016).

The fact icebergs are more likely to deliver freshwater to the interior of the Labrador Sea does not imply that ICB has shallower mixed layer depths (MLDs) or weaker subduction rates throughout the simulation (Figures 9a and 9c). The freshwater content in the Labrador Sea is still dominated by larger liquid runoff rates from Greenland compared to solid discharge, and by increased Arctic freshwater export through Fram Strait, which can be exchanged with the interior of the Labrador Sea along Greenland's southwestern shelf.

In Marsh et al. (2015), March MLD is actually shallower in the iceberg run by ~100 m in the Labrador Sea. Merino et al. (2016) also noted shallower MLD in the Southern Ocean associated with iceberg freshwater release. The difference in those results might be associated with different atmospheric forcing, different Greenland discharge rates and locations, different ocean model parameters, and the fact that they do not integrate ocean fields from surface to iceberg keel before using them in the iceberg module (Marson et al., 2018).

5. Icebergs take up latent heat from the ocean
The take up of heat from the ocean led to an increased sea ice coverage (especially in Baffin Bay, Figure 5c), which in turn likely reduces the evaporation (Jongma et al., 2009), making this version of iceberg model fresher than its corresponding "no heat flux" version (Figure S4). In a set of 3°-resolution simulations, Bügelmayer et al. (2015) also found an increase in sea ice thickness north of Baffin Bay associated with the explicit representation of icebergs. The additional freshwater that results from reduced evaporation seems to overcome the cooling effect of latent heat take up in aspects such as the reduced MLD and decreased freshwater content associated with slower melt.
6. The Gulf Stream position might be affected by the way Greenland's discharge is parameterized in ocean models
We detected an increased volume flux of Slope Water into the Gulf of Saint Lawrence in ICB, resulting in local warming at depth. The cause of this increased influx of warm waters is not yet clear, but might be associated with the intensity and shelf proximity of the Gulf Stream (see Figure 11), a subject still open for investigation. Warming of the northwest Atlantic shelf has in fact been observed along with a decrease in saturation oxygen concentration, and it has been linked to the retreat of the Labrador Current and advance of the Gulf Stream at the tail of the Grand Banks due to wind stress changes (Claret et al., 2018). Here, a new possibility arises that this circulation change might be partially associated with Greeenland discharge.

We highlight that increasing the model resolution might change the results presented, since eddies play an important role bringing liquid freshwater to the Labrador Sea (Marsh et al., 2010; Pennelly et al., 2019). Additionally, Enderlin et al. (2016) pointed out that 10–50% of the icebergs melt inside the fjords (not resolved in our 1/4° simulations), which means we might be overestimating the mass of solid freshwater entering open ocean. We also point out that, with few exceptions, most of the observed differences between ICB and LIQ are small and within their interannual variability. However, this sensitivity study is useful to show where changes could be expected should Greenland mass loss increase and/or the ratio between solid discharge and liquid runoff be altered. Levine and Bigg (2008) showed that, although iceberg discharge produces similar results to homogeneous freshwater input over a large area considering its current small magnitude, under larger discharges iceberg representation becomes important in order to ease the freshwater flux into the ocean by gradually melting and producing a less dramatic impacts on the circulation. Moreover, in the northwest sector of Greenland, calving is already pointed out as the largest contributor to ablation (Wood et al., 2018). If this trend is followed by other sectors, the accessibility of icebergs to the interior subpolar gyre should play a more important role on deep ocean convection.

We conclude that the choice of explicitly representing icebergs in an ocean model depends on the user's tools and goals. For example, Weijer et al. (2012) pointed out that, in coarse resolution models, the MOC is rather insensitive to different methods used to prescribe Greenland runoff. But while differences might be small enough to be ignored in large-scale studies with low resolution simulations, they might become important for regional freshwater budgets, circulation, and sea ice thickness. As for using latent heat flux in the iceberg model or not, we find that the heat take-up will make a difference in the regional sea ice thickness and freshwater content. Bügelmayer et al. (2015) highlight that the most important impacts of icebergs on the ocean are associated with their take up of latent heat rather than their freshwater flux. We argue that both iceberg contributions are important, but including latent heat flux brings the results (especially regarding freshwater content) closer to the ones obtained by an all-liquid discharge representation.

Data Availability Statement

The simulations can be accessed at https://doi.org/10.7939/DVN/YEHVXO (LIQ), https://doi.org/10.7939/DVN/RQSO6G (ICB), https://doi.org/10.7939/DVN/MEOB7M ($ICB_{no\ heat\ flux}$), and https://doi.org/10.7939/DVN/DL-B3HK (ICB_{tracer}).

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