A subtropical fate awaited freshwater discharged from glacial Lake Agassiz

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[1] The 8.2 kyr event is the largest abrupt climatic change recorded in the last 10,000 years, and is widely hypothesized to have been triggered by the release of thousands of kilometers cubed of freshwater into the North Atlantic Ocean. Using a high-resolution (1/6°) global, ocean-ice circulation model we present an alternative view that freshwater discharged from glacial Lake Agassiz would have remained on the continental shelf as a narrow, buoyant, coastal current, and would have been transported south into the subtropical North Atlantic. The pathway we describe is in contrast to the conceptual idea that freshwater from this lake outburst spread over most of the sub-polar North Atlantic, and covered the deep, open-ocean, convection regions. This coastally confined freshwater pathway is consistent with the present-day routing of freshwater from Hudson Bay, as well as paleoceanographic evidence of this event. Using a coarse-resolution (2.6°) version of the same model, we demonstrate that the previously reported spreading of freshwater across the sub-polar North Atlantic results from the inability of numerical models of this resolution to accurately resolve narrow coastal flows, producing instead a diffuse circulation that advects freshwater away from the boundaries. To understand the climatic impact of freshwater released in the past or future (e.g. Greenland and Antarctica), the ocean needs to be modeled at a resolution sufficient to resolve the dynamics of narrow, coastal buoyant flows.
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1. Introduction

[2] Around 8,160–8,740 years ago, as the Laurentide Ice Sheet (LIS) gradually receded, an estimated 163,000 km^3 of freshwater are thought to have been abruptly discharged into Hudson Bay, Canada, as an ice-dam at the eastern margin of glacial Lake Agassiz suddenly failed [*Barber et al.*, 1999; *Clarke et al.*, 2004] (Figure S1 of the auxiliary material).[1] The timing of this event appears to coincide with the strongest observed cooling recorded in the North Atlantic region over the last 10,000 years, and is referred to as the '8.2-kyr-event' [*Alley and Agustsdottir*, 2005]. It has been widely assumed that as freshwater flowed away from Hudson Bay it spread eastwards to cover the surface of the central Labrador Sea, the North Atlantic sub-polar gyre, and central Greenland Seas, forming a fresh, buoyant surface layer that inhibited the formation rate of the dense water responsible for the production of North Atlantic Deep Water (NADW) [*Alley and Agustsdottir*, 2005]. It is this reduction in convective activity that is thought to have weakened the poleward heat transport of the Atlantic Meridional Overturning Circulation (AMOC), and initiated the abrupt cooling recorded around the North Atlantic region at that time [*Barber et al.*, 1999; *Teller et al.*, 2002].

[3] Numerical modeling studies have repeatedly simulated the weakening of the AMOC, and the climatic cooling associated with this event by gradually releasing freshwater previously stored in Lake Agassiz over either, the North Atlantic between 50°N–70°N (in a type of experiment frequently referred to as 'hosing') [*Bauer et al.*, 2004; *Stouffer et al.*, 2006], or directly over the central Labrador Sea [*Renssen et al.*, 2002]. In these experiments, however, little regard was given to the circulation dynamics transporting freshwater to these regions of the North Atlantic [*Wunsch*, 2010]. Although more realistic simulations of the 8.2-kyr-event have initially placed the freshwater closer to its source [*Clarke et al.*, 2009; *LeGrande et al.*, 2006], we show here that the horizontal grid resolutions utilized by many studies were too coarse to sufficiently resolve the components of the near-shore ocean circulation necessary to accurately model the transport of the freshwater pulse. It is the aim of this paper to show that by resolving narrow coastal currents, shelf-breaks and strong frontal zones, the conceptual ideal that freshwater from glacial Lake Agassiz once covered the entire sub-polar North Atlantic is probably inaccurate. This finding has important ramifications for how the scientific community should go about introducing freshwater to the North Atlantic region in numerical climate simulations investigating abrupt climate change.

2. Model and Experiment Design

[4] To more accurately model the pathway that freshwater discharged into Hudson Bay from glacial Lake Agassiz would have taken en-route to the North Atlantic at the time of the 8.2-kyr-event, we use a high-resolution (1/6°, ~18 km) eddy-permitting, global, coupled ocean-ice numerical circulation model, based on the MITgcm (Figure S2) [*Marshall et al.*, 1997]. By integrating our model at a resolution that is approx. 5 to 20 times higher than the majority of previous models investigating this glacial outburst flood, we are working at a resolution that accurately resolves narrow coastal currents, shelf-breaks and strong frontal zones. To simulate the flood event we released 5 Sv (1 Sv ≡ 10^6 m^3 s^{-1}) of freshwater in the southwestern corner of Hudson Bay for

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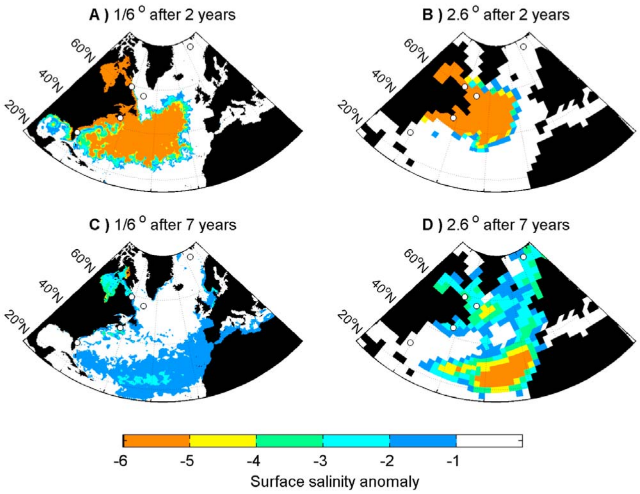

Figure 1. Surface salinity anomalies (perturbation - control) (a and b) two and (c and d) seven years after the freshwater pulse was released in the high- (Figures 1a and 1c) and coarse- (Figures 1b and 1d) resolution integrations. After 7 years, freshwater is confined to the sub-tropical gyre (20°N–40°N) in the high-resolution integration (Figure 1c) and to the sub-polar gyre (50°N–70°N) in the coarse-resolution integration (Figure 1d). Filled white circles refer to locations in Figure 2.

one year, based on recent hydrological modeling estimates [*Clarke et al.*, 2004]. To draw attention to the importance of resolving this flood event at a high spatial resolution, in a second experiment we reduced our models horizontal resolution to 2.6° to make it comparable to existing studies simulating this freshwater outburst, while retaining the point source outflow location. In all of our experiments we do not seek to reproduce the full, coupled climatic impact of the 8.2-ky-event, but instead focus on understanding the pathways taken by freshwater discharged into the North Atlantic.

3. Results

[5] In our high-resolution numerical integration we found that once the freshwater pulse left Hudson Bay it turned sharply to the right, and stayed on the Labrador shelf as a buoyant, coastal current, with a width of 40–100 km, and a vertical thickness of 70–100 m (Figure 1). The freshwater rapidly propagated south with an average speed of 1.9 ± 0.3 m s^{-1}, causing the surface salinity on the northern Labrador shelf to abruptly freshen by 30 psu (from 32 to 2 psu) 2 months after the initial outburst (Figure 2). The characteristics of the freshwater pulse agree with theoretical studies of buoyant gravity currents along a sloping bottom [*Lentz and Helfrich*, 2002], and imply that a freshwater pulse of this nature would have had a width of 59 km, i.e. of the same order of magnitude as the width of the Labrador shelf (95–175 km), a thickness of 75 m, and a propagation speed of 2.3 m s^{-1}.

[6] The freshwater pulse reached the complex bathymetry of the Grand Banks in just over one month (Figure 2), and exerted a considerable amount of buoyancy forcing on the Gulf Stream system, as seen by the large horizontal shear and eddy-shedding in this region (Figure 1). 54% of the freshwater pulse was deflected offshore in a jet-like spout, where it entrained and mixed with the northward-flowing Gulf Stream, much like the present day circulation [*Fratantoni and McCartney*, 2010], but on a larger spatial scale, and become routed into the sub-tropical gyre (Figure 1). Four years after the initial outburst, surface salinities between 20°N–40°N (i.e. the subtropical North Atlantic) were lowered by 3 to 5 psu (Figure S3); further north in the sub-polar gyre, where we might have expected large changes in salinity to have occurred, there was no evidence of the freshwater outburst. In the central Labrador Sea, at the former site of Ocean Weather Ship (OWS) Bravo (56.5°N, 51°W) where open-ocean convection has historically been observed [*Lazier*, 1980], we found no evidence of the freshwater outburst based on changes in surface salinity (Figure 2d). In the central Greenland Sea, where deep, open-ocean, convection is thought to have primarily occurred in the early Holocene [*Hillaire-Marcel et al.*, 2001], there was also no evidence of the freshwater outburst.

[7] The part of the freshwater outburst that was not mixed and advected with the Gulf Stream flowed southward along the east coast of North America, inshore of the Gulf Stream,

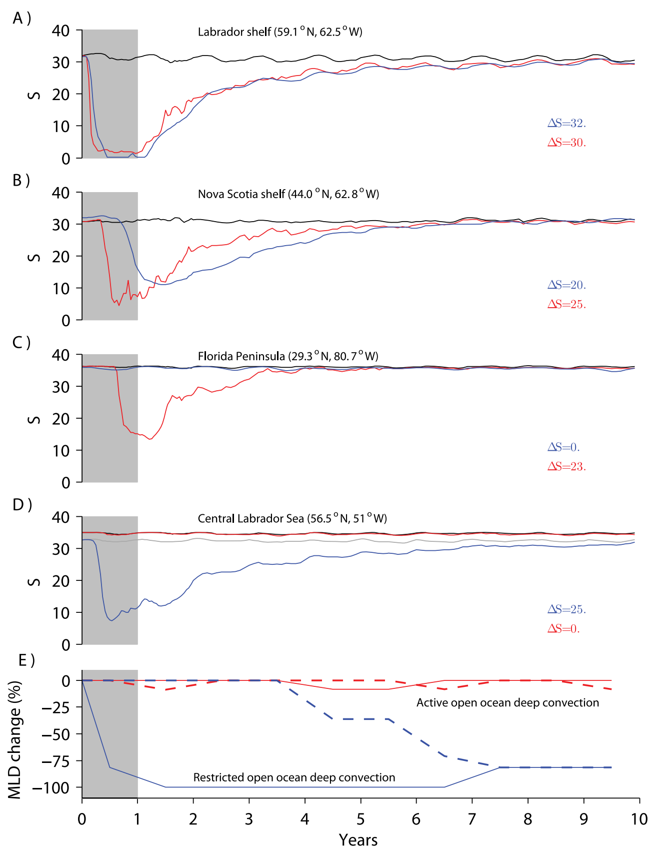

Figure 2. Surface salinity time series from the (a) Labrador shelf, (b) Nova Scotia shelf, (c) Florida Peninsula, and (d) central Labrador Sea. (e) Percentage change in maximum mixed layer depth (MLD) in the Labrador and Greenland Seas. Gray shading is the freshwater release period. In Figures 2a–2d, (Black) high-res. control, (Gray) coarse-res. control, (Red) high-res. perturbation, (Blue) coarse-res. perturbation. ΔS is the maximum salinity change between the control and perturbation experiments. In Figure 2e, Red (Blue) lines refer to the high (coarse) resolution integrations, and solid (dashed) lines refer to the Labrador (Greenland) Seas.

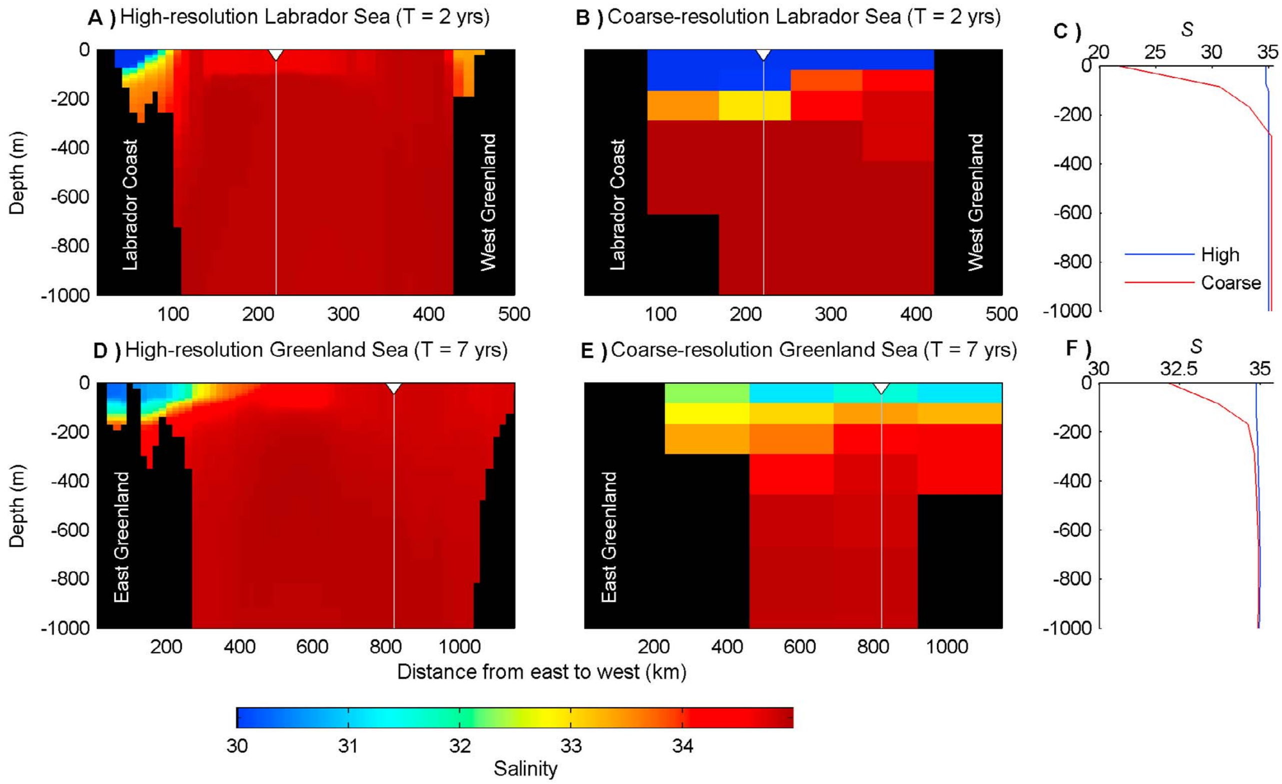

Figure 3. Salinity cross section for the (a and d) high- and (b and e) coarse-resolution integrations, for the Labrador Sea (AR7W) and Greenland Sea (75°N) 2 and 7 years, respectively, after the freshwater release. At high-resolution there is no freshening beyond the shelf in either basin (Figures 3a and 3d). At coarse-resolution the entire Labrador Sea (to depth ~100 m) is covered by a freshwater layer (Figure 3b). A freshwater 'cap' is also observed ~400 km offshore of E. Greenland at this resolution (Figure 3e). Vertical salinity, *S*, profiles from the Labrador (OWS Bravo) and Greenland (75°N, 7.5°E) Seas are shown by white triangles and vertical lines (Figures 3a, 3b, 3d, and 3e), and displayed (Figures 3c and 3f) to highlight changes in vertical stratification.

as a concentrated coastally-trapped current. The surface salinities off the coast of Nova Scotia were reduced by 25 psu (from 30 to 5 psu) 6 months after the initial freshwater outburst, and by 23 psu (from 36 to 13 psu) 8 months later at the southern tip of Florida (Figure 2c).

[8] Repeating the same freshwater discharge experiment using our coarse-resolution configuration led to a considerably different, and more typical [*Li et al.*, 2009; *Renssen et al.*, 2002] pathway for the outburst event (Figures 1 and S3). Upon leaving Hudson Strait, the freshwater was quickly advected offshore towards the central Labrador Sea where it caused the surface salinity in this region to be reduced by up to 25 psu (from 32 to 7 psu) after only 6 months (Figure 2d). The freshwater then propagated across the North Atlantic, north of 40°N. At the site of Greenland Sea deep convection in our model (75°N, 7.5°E) surface salinities were reduced by >1 psu 7 years after the initial freshwater outburst, and remained this fresh until the end of the integration. The freshwater outburst had only a limited penetration south of the Grand Banks, compared to our high-resolution integration, with no evidence of this event at the southern tip of Florida (Figure 2c). In-other-words, the freshwater outburst in this model configuration covered the region commonly 'hosed' by AMOC-freshwater modeling sensitivity studies (50°N–70°N) (Figure 1).

[9] Changes in the annual maximum mixed layer depth in the central Labrador and Greenland Seas (See Section 3 of Text S1 for Mixed layer Depth calculation) in both of our model configurations reflect the changes we observed in the surface salinities (Figure 2e). In our high-resolution integration, the maximum mixed layer depth in both of these seas shoaled by less than 10%, yet continued to exceed 3000 m, implying that significant open-ocean deep convection persisted throughout the North Atlantic in the decade following the freshwater outburst. In contrast, the mixed layer depth in our coarse-resolution integration was rapidly restricted to the surface in the Labrador Sea, and more gradually reduced in the Greenland Sea 4 years later. During the last 3 years of our coarse-resolution integration, the persistence of an extremely shallow mixed layer in both the Labrador and Greenland Seas (<85 m) points to the fact that there was no deep, open-ocean, convection in either of these regions at this time in this model configuration.

[10] An east-west transect across the Labrador Sea (Figure 3) shows clearly that in our high-resolution integration the freshwater outburst is confined to the shelf as a buoyant, coastal current, with limited penetration into the central Labrador Sea. In contrast, our coarse-resolution integration reveals a 10 psu freshening in the upper 200 m of the water column, creating a freshwater 'cap' that per-

sists for the entire ten-year model integration. A similar picture for the Greenland Sea is observed 7 years after the freshwater pulse was released: in our high-resolution integration the properties of the water column remained unchanged as the freshwater was routed far to the south, while in our coarse-resolution integration this region became covered with a freshwater layer that reduced the surface salinity by up to 3 psu, and extended across the Greenland Sea at 75°N.

4. Discussion

[11] The pathway taken by the freshwater from Hudson Bay to the North Atlantic was considerably different when the same model was integrated at two different spatial resolutions. The differences primarily result from our high-resolution configuration resolving to a significantly greater accuracy, the narrow coastal currents and frontal boundaries that separate the shelf waters from the interior [*Myers*, 2005]. When we reduce the model's spatial resolution we are no longer resolving these features, creating a broader, more diffusive Labrador Current that allows the freshwater outburst to be advected into the central Labrador Sea and sub-polar gyre. The different advective pathways coupled with the differing abilities of the two model resolutions to capture mesoscale ocean dynamics causes the freshwater anomaly to persist longer in our coarse-resolution integration (Figure S3); in our high-resolution integration, advection of the freshwater directly into the Gulf Stream and increasingly realistic circulation dynamics cause the buoyant flow to mix more rapidly with the ambient ocean.

[12] The pathway of the freshwater outburst along the Labrador Shelf in our high-resolution integration is substantiated by the present-day route taken by freshwater traveling from Hudson Bay to the Grand Banks and the Gulf Stream [*Straneo and Saucier*, 2008]. This route is also supported as a pathway for the outburst flood by the presence of a carbonate-rich layer extending along the Labrador shelf from Hudson Strait [*Hillaire-Marcel et al.*, 2007], and by a reduction in shelf salinity as far south as Cape Hatteras (based on changes in foraminifera) in cores recovered from the northwest Atlantic dated to ~8,200 years ago [*Keigwin et al.*, 2005]. We draw attention to the fact that the lower salinity values occurred only in cores retrieved from the continental shelf; cores drilled offshore of the Labrador Current showed no evidence for a similar salinity reduction in the central Labrador Sea at this time. This is consistent with our high-resolution model results.

[13] Several coupled numerical model simulations have shown an intensification of the mid-latitude westerly wind in response to the 8.2-kyr-event that increased the advection of freshwater across the sub-polar gyre [*Clarke et al.*, 2009]. We investigated the sensitivity of the coastal buoyant flow to the strength of the offshore winds in three separate regional experiments: i) a no-wind case, ii) our standard forcing, and iii) a constant offshore wind stress of 15 m s^{-1} along the Labrador coast, and found that the downstream propagation of the freshwater was almost identical in all cases. In each experiment, the freshwater remained confined to the Labrador Shelf due to the persistence of the strong frontal zone at the shelf break, and resulted in the flow propagating virtually unaffected towards the Grand Banks.

[14] The agreement of our high-resolution model with fluid dynamics experiments, present-day circulation dynamics, and paleoceanographic observations, leads us to conclude that in all likelihood the freshwater discharge from glacial Lake Agassiz would have been routed into the subtropical gyre, and would not have spread over the sub-polar North Atlantic and the present day open-ocean deepwater convection sites. From this finding it is trivial to suggest that the freshwater outburst did not reduce the formation of NADW and slow the AMOC; indeed, when a volume of freshwater equivalent to the 8.2-kyr-event was released south of the Grand Banks in a modeling study [*Li et al.*, 2009], the climatic impacts were considerably less than when the same freshwater outburst was released further north.

[15] To make any statements regarding the climatic impact of the freshwater pathway we have described would, however, be unwise without further substantiation of our results, particularly as our model is not coupled to an active atmosphere. In a recent study by *Clarke et al.* [2009] it was speculated that a high suspended sediment load in the outburst flood may have caused the flow to become hyperpycnal and altered its pathway by causing the freshwater to sink, and remain at depth. Furthermore, the changes that occurred in the circulation of the North Atlantic Ocean in the early Holocene are far from clear at the moment; while there is evidence from sediment cores recovered in the sub-polar North Atlantic to suggest that a reduction in NADW production, and a weakening of the AMOC, did indeed occur at this time [*Ellison et al.*, 2006; *Kleiven et al.*, 2008], additional proxy evidence tends to argue that the observed changes were part of a multi-century climate deterioration that cannot be entirely attributed to the disruption of NADW formation [*Rohling and Palike*, 2005].

[16] The freshwater pathway depicted by our high-resolution model changes our understanding of how freshwater from the 8.2-kyr-event would have been transported around the ocean. The lack of evidence for any freshwater from the outburst flood in the present-day deep convection sites is intriguing, and could imply that the interplay between freshwater and the climate system is inherently more complicated than simply 'capping' the convective regions. Indeed, convection along the boundary currents in the Labrador Sea now appears to play an important role in the deep circulation, but it is a process still unresolved in numerical circulation models [*Spall*, 2008]. It is apparent, however, that initially spreading freshwater over the surface of the sub-polar North Atlantic (50°N–70°N) in numerical 'hosing' experiments tends to introduce freshwater into areas of the ocean that it would have had considerable difficulty reaching at this time when one considers ocean circulation dynamics.

[17] In closing, we emphasis that the initial confinement of a freshwater pulse to the coastal boundary current system as modeled here, applies not only to the 8.2-kyr-event, but also to any location where freshwater is being discharged directly into the coastal ocean. This is especially relevant to the freshwater pulses that occurred around the time of the Preboreal Oscillation and the Younger Dryas, as well as the current release of freshwater from the melting of the Greenland and Antarctic Ice Sheets. To disentangle the climatic role of freshwater, the challenge is to model the ocean for longer (10^2–10^3 years) periods of time at a resolution sufficient to resolve narrow, coastal buoyant flows.

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