Meltwater routing and the Younger Dryas

Alan Condron[a,1] **and Peter Winsor**[b]

[a]Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst, MA 01003; and [b]Institute of Marine Science, School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK 99775

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The Younger Dryas—the last major cold episode on Earth—is generally considered to have been triggered by a meltwater flood into the North Atlantic. The prevailing hypothesis, proposed by Broecker et al. [1989 *Nature* 341:318–321] more than two decades ago, suggests that an abrupt rerouting of Lake Agassiz overflow through the Great Lakes and St. Lawrence Valley inhibited deep water formation in the subpolar North Atlantic and weakened the strength of the Atlantic Meridional Overturning Circulation (AMOC). More recently, Tarasov and Peltier [2005 *Nature* 435:662–665] showed that meltwater could have discharged into the Arctic Ocean via the Mackenzie Valley ∼4,000 km northwest of the St. Lawrence outlet. Here we use a sophisticated, high-resolution, ocean sea-ice model to study the delivery of meltwater from the two drainage outlets to the deep water formation regions in the North Atlantic. Unlike the hypothesis of Broecker et al., freshwater from the St. Lawrence Valley advects into the subtropical gyre ∼3,000 km south of the North Atlantic deep water formation regions and weakens the AMOC by <15%. In contrast, narrow coastal boundary currents efficiently deliver meltwater from the Mackenzie Valley to the deep water formation regions of the subpolar North Atlantic and weaken the AMOC by >30%. We conclude that meltwater discharge from the Arctic, rather than the St. Lawrence Valley, was more likely to have triggered the Younger Dryas cooling.

abrupt climate change | climate modeling | paleoclimate

The sudden release of meltwater from glacially dammed lakes located along the southern margin of the Laurentide Ice Sheet (LIS) is frequently cited as the main trigger for the Younger Dryas (YD) (1, 2)—a 1,200-y-long cold episode that began 12.9 kya (3). The basic premise suggests that at the onset of this sudden climatic transition, glacial runoff switched from the Gulf of Mexico to a more northerly outlet to allow thousands of cubic kilometers of meltwater to rapidly drain into the North Atlantic (1, 4) (Fig. 1). It was originally hypothesized by Broecker et al. (1) that the subsequent freshening of the subpolar North Atlantic suppressed the sinking limb of the Atlantic Meridional Overturning Circulation (AMOC) and reduced the northward transport of heat to the poles. As a result of a weakened AMOC, the relatively warm climate of the Allerød episode abruptly ended and the YD began. This original meltwater diversion hypothesis focused on the likelihood that Lake Agassiz supplied freshwater to the ocean through an "eastern outlet," allowing meltwater to enter the North Atlantic via the St. Lawrence Valley (1, 4, 5).

Since then, several studies have questioned the St. Lawrence Valley as a feasible drainage route to the ocean. Using dinoflagellates to reconstruct sea surface salinity at the mouth of the Gulf of St. Lawrence, de Vernal et al. (6) were forced to reject an eastern route based on a lack of evidence that the surface waters in this region freshened at the onset of the YD. A subsequent search for a freshwater signal in this location by Carlton et al. (5) found that, by correcting a planktonic foraminifera record for sea surface temperature and salinity effects using the existing sea surface temperature record from de Vernal et al. (6), a freshwater signal become apparent in the Gulf of St. Lawrence. From this, they concluded that meltwater had in fact been routed to the St. Lawrence Valley at the start of the YD. In a short reply that followed this study, Pelter et al. (7) argued that the salinity drop they had identified might have been artificial and caused by using one proxy to correct another. A separate reconstruction of the drainage chronology of North America by Tarasov and Peltier (8) found that rather than being to the east, the geographical release point of meltwater to the ocean at this time might have been toward the Arctic. Further support for a northward drainage route has since been provided by Peltier et al. (9). Using a numerical model, the authors showed that the response of the AMOC to meltwater placed directly over the North Atlantic (50° N to 70° N) and the entire Arctic Ocean were almost identical. This result implies that meltwater released into the Arctic might be capable of cooling the climate system to the same extent as meltwater released over the North Atlantic. Moreover, Broecker and colleagues (10, 11) have started to question the feasibility of the eastern outlet as a trigger for the YD based on existing geomorphological evidence, and now suggest that an alternative drainage route is required (12). In 2010, Murton et al. (13) presented evidence from sedimentary stratigraphy in the Mackenzie Delta region that strongly supports the notion that the onset of the YD coincides with a meltwater discharge into the Arctic Ocean via the Mackenzie Valley (Fig. 1).

Identifying the location where the meltwater flood entered the ocean at the onset of the YD is vital for understanding the sensitivity of the climate system to sudden increases in the delivery of freshwater to the ocean. Although the frequently cited hypothesis of Broecker et al. (1) is elegant in its simplicity, it has yet to be verified whether the St. Lawrence Valley can deliver enough meltwater to the subpolar North Atlantic deep water formation regions to significantly weaken the AMOC. Although the recent drainage basin model of Tarasov and Peltier (8) found that the onset of the YD coincides with a large meltwater discharge to the Arctic Ocean, the absence of an ocean component in this model meant that changes in deep convection, and the response of the AMOC to this meltwater, could not be directly tested.

Here we determine the potential of these two meltwater routes to weaken the AMOC by using a state-of-the-art, high-resolution (1/6°, ∼18 km), global coupled ocean sea-ice circulation model [Massachusetts Institute of Technology general circulation model, MITgcm (14); see *Methods*]. This model captures the circulation of the ocean and sea ice at 10–15 times higher resolution than previous models attempting to understand how meltwater acts to trigger the YD (9, 15). We discharge a volume of meltwater that is larger than the reconstructed volume discharged from Lake Agassiz at this time (2) because we expect the main meltwater source to have been the large Keewatin ice dome located over the northwestern part of the LIS, as was found by Tarasov and Peltier (8). In all of our experiments, we do not, however, seek to reproduce the full, coupled climatic impact of the YD, but instead to focus on understanding the influence of the geographically different discharge locations on deep convection and the strength of the AMOC.

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[1] To whom correspondence should be addressed. E-mail: acondron@geo.umass.edu.

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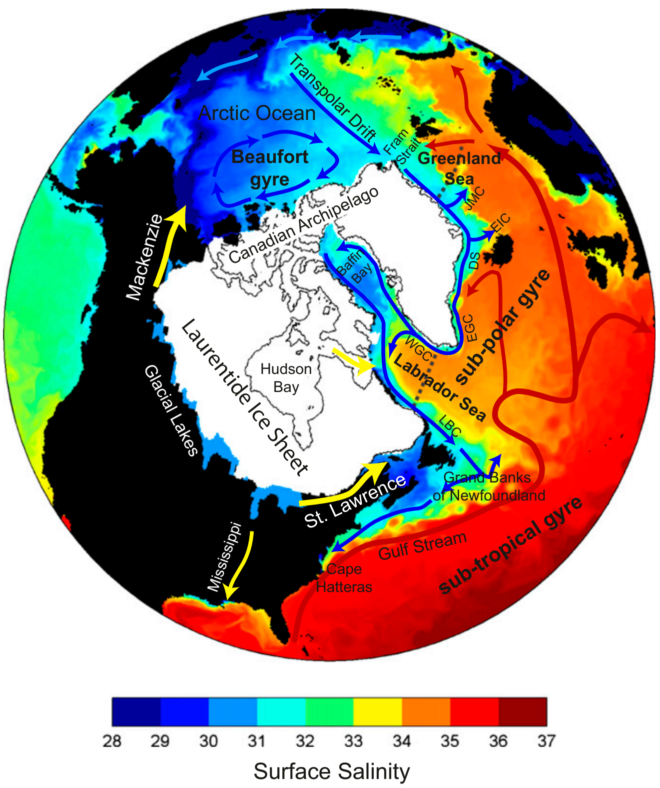

Fig. 1. The drainage pathways of meltwater stored in glacial lakes located along the southern margin of the Laurentide Ice Sheet. The direction of meltwater drainage is shown by the yellow arrows. The approximate position of the ice sheet is shown (in white) just before the onset of the Younger Dryas. The ocean colors are surface salinity from the control integration (1/6° resolution) with warm (cold) surface currents shown in red (blue). Gray dashed lines across the Labrador and Greenland Seas are the locations of the two cross-sections shown in Fig. 3. DS, Denmark Strait; EIC, East Icelandic Current; JMC, Jan Mayen Current; LBC, Labrador Current.

We release 5 Sv (Sv = 10^6 m^3s^{-1}) of meltwater for 1 y at the mouth of the St. Lawrence Valley and Mackenzie Valley in two separate 25-y-long perturbation experiments to simulate an abrupt meltwater event and its effect on ocean circulation. Our choice of a 1-y flood duration is based on prior work (2, 13), but we cannot rule out the possibility that meltwater might have been routed down the Mackenzie Valley for the entire duration of the YD, or until isostatic rebound raised the height of the outlet enough so that meltwater reached the ocean via a different route. In such a scenario, we expect that the meltwater event might have produced a flood hydrograph, with the most intense flow occurring at the start.

In the first two experiments, topography is configured for a modern-day ocean to allow flow between the Arctic and North Atlantic through the Canadian Arctic Archipelago (CAA). We undertake a second Arctic meltwater discharge experiment with the CAA closed to understand how glacial ice restricting flow through this region during the YD alters the impact of meltwater on the AMOC (Fig. 1). Each experiment starts from modern-day ocean (salt and temperature) conditions that, before any meltwater discharge, have wintertime open-ocean deep convection occurring in the Labrador and Greenland Seas. Given that the main aim of our model integrations is to understand the advection pathways of meltwater in the ocean, and that the outburst event occurred at the end of the Bølling-Allerød warm episode when the strength of the AMOC was close to modern conditions (16), we expect our modern climate model simulations to be representative of those found at the onset of the YD.

Our experimental setup is specifically designed to understand the sensitivity of the climate system to meltwater discharge from two geographically different outlets. The majority of previous modeling studies (9, 15), including those undertaken by the Paleo-Modeling Intercomparison Project (17), tried to investigate the relationship between meltwater and abrupt climate change by placing additional freshwater uniformly over a large region of the subpolar North Atlantic (e.g., 50° N to 70° N), in so-called “hosing” experiments. To date, only a limited number of modeling experiments have tried releasing meltwater into the ocean close to its geographical discharge point (18–20). However, when meltwater is released in this realistic way, the response of the climate system to any additional freshwater is very sensitive to the initial discharge location (20). To more accurately simulate the response of the AMOC to freshwater, we introduce meltwater at geographically correct locations (i.e., river mouths) and allow it to realistically advect away from its source and circulate the ocean.

In addition to inaccurately releasing meltwater spatially into the ocean, previous modeling efforts were often too coarse (~1–3° spatial resolution) to fully resolve the near-shore boundary currents and shelf morphology essential for realistically simulating the transport and advection of meltwater around the ocean margins (9, 15, 17). Resolving these narrow boundary currents in our ocean model at the onset of the YD is important for correctly simulating the delivery of meltwater to the open ocean, deep convection regions that drive the AMOC. Recently, Condron and Winsor (19) found that meltwater discharged from Hudson Bay into both a coarse (2.8°) and high (1/6°) spatial resolution configuration of the same model reached the central Labrador Sea convection region only in the coarse resolution configuration. This result was found to be due to the poorly resolved, overly diffusive nature of the near-shore Labrador Current at that resolution. In contrast, when the Labrador Current was resolved by the high-resolution configuration, meltwater did not move offshore into the convection region, but remained confined to the Labrador Current until it reached the Grand Banks of Newfoundland.

Results

We find that meltwater from the St. Lawrence Valley does not cover the subpolar North Atlantic with a layer of freshwater, similar to the subpolar freshening hypothesis of Broecker et al. (1). Instead, as meltwater leaves the Gulf of St. Lawrence, it turns to the right (because of the Coriolis force) much like the present-day circulation (21) and flows south along the east coast of North America. The meltwater remains on the continental shelf as a buoyant coastal current (with a width of ~120 km) until entrainment with the northward-flowing Gulf Stream at Cape Hatteras advects it into the subtropical gyre (20° N to 40° N). This location is ~3,000 km south of both the subpolar gyre and traditional hosing region (Fig. 2*A*; Fig. S1).

When the CAA is open, meltwater from the Mackenzie Valley flows through the archipelago into Baffin Bay and reaches the Labrador Current after ~6 mo. The meltwater does not penetrate into the central Labrador Sea where deep convection occurs, but remains confined to the Labrador Shelf as a narrow (~70 km wide), buoyant, coastal current. At the Grand Banks, the meltwater entrains and mixes with the northward flow of the Gulf Stream in a realistic fashion that agrees closely with modern-day observations (22). The meltwater deflects offshore in a jet-like spout and advects into the subtropical gyre (20° N to 40° N) (Fig. 2*B*). Approximately 40% of the original meltwater flood is not transported through the CAA, but advects eastward along the Arctic shelf toward the Queen Elizabeth Islands and the north coast of Greenland. After 4 mo, the meltwater reaches Fram Strait and leaves the Arctic confined to the East Greenland Current (EGC). There is little offshore penetration of the meltwater into the Nordic Seas (Greenland, Iceland, Norwegian Seas) until it reaches the Jan Mayen and East Icelandic currents to the south.

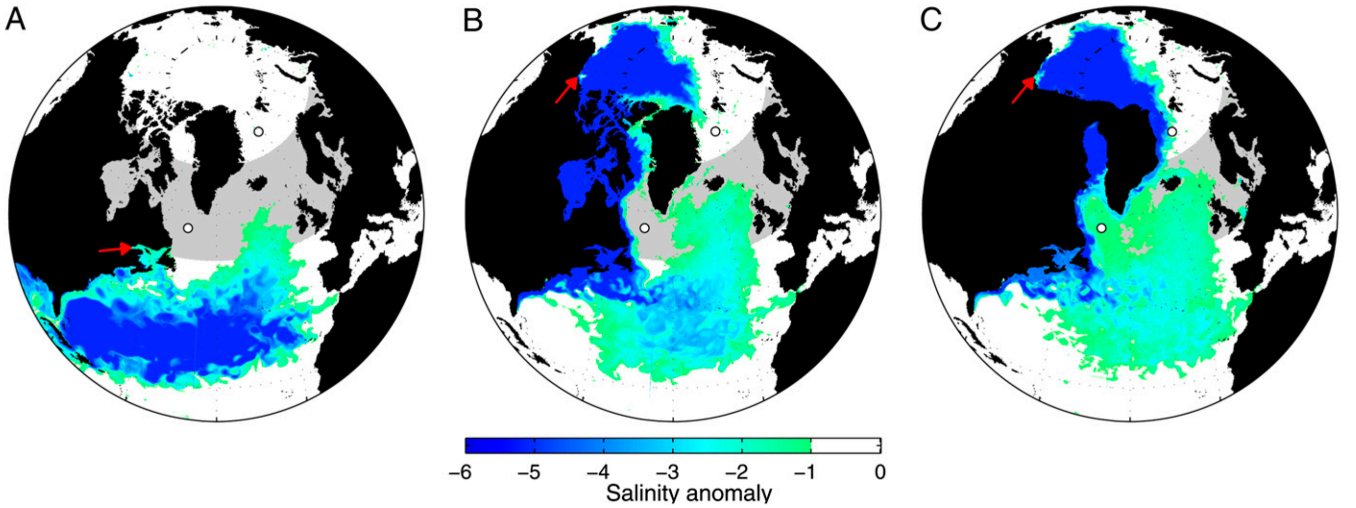

Fig. 2. The dispersal of meltwater in the North Atlantic. The colors (green-blue) show the difference in surface salinity (perturbation minus control) in response to releasing meltwater from the (*A*) Gulf of St. Lawrence and (*B* and *C*) Mackenzie Valley with the CAA (*B*) open and (*C*) closed. The snapshots are drawn 32, 43, and 56 mo, respectively, after the meltwater release and coincide with the time of maximum surface freshening. Red arrows are the discharge locations. White circles are locations where open-ocean deep convection has been observed (30) in the modern-day ocean: Ocean Weather Station Bravo (56.5° N, 51° W) and Greenland Sea (75° N, 3° W). The gray shading (50° N to 70° N) is the traditional climate model meltwater hosing region.

Here, these eastward-flowing currents allow meltwater to freshen the surface of the Nordic Seas by ∼1 practical salinity units (psu). Meltwater that remains in the EGC passes around the southern tip of Greenland and flows northward in the West Greenland Current (WGC). At ∼61° N, boundary current eddies (23) not previously resolved by coarser resolution climate models shed meltwater from the WGC into the central Labrador Sea to freshen the surface waters of this open ocean, deep convection site by >1 psu (Fig. 3 *B* and *D*). Meltwater that remains in the WGC continues northward, circulates Baffin Bay, and joins meltwater that advects directly through the CAA (Fig. S1).

With the CAA blocked by the LIS, the entire meltwater flood is forced to exit the Arctic at Fram Strait (Fig. 2*C*). The increase in the southward transport of meltwater in the EGC (compared with the when the CAA is open) increases the supply of meltwater to the Nordic Seas and freshens the surface of the Greenland Sea by ∼2 psu (Fig. 3 *G* and *H*). The larger volume of meltwater reaching the WGC enables the boundary current eddies shedding from this current to freshen the surface of the central Labrador Sea by up to 3 psu (Fig. 3 *C* and *D*). Meltwater that remains in the WGC circulates Baffin Bay, joins the southward-flowing Labrador Current, and reaches the Grand Banks ∼1 y after the initial onset of the flood. At the Grand Banks, the meltwater undergoes intense mixing with the Gulf Stream that (once again) advects it offshore into the subtropical gyre (Fig. S1).

In the central Arctic, the anticyclonic circulation of the Beaufort Gyre acts to store meltwater from the Mackenzie Valley (Fig. 2 *B* and *C*). The meltwater circulates the gyre and after ∼3 y begins a gradual release to the subpolar North Atlantic, in the Transpolar Drift. The slow release of meltwater south through Fram Strait provides a mechanism unique to the Arctic that is capable of turning a short-duration (∼1 y), high-magnitude meltwater discharge event into a significantly longer, more moderated and sustained meltwater rerouting event, to the North Atlantic. The ability of this model to realistically store and release Arctic freshwater to the North Atlantic has previously been demonstrated (24). We find that when the CAA is closed, the southward transport of meltwater at Fram Strait remains >3 times higher than the control experiment after 25 y of model integration (Fig. S2). There is no comparable mechanism in the North Atlantic to locally store and gradually release meltwater discharged from the St. Lawrence Valley to the open-ocean deep convection regions. In fact, intense mixing with the Gulf Stream rapidly diffuses meltwater from the St. Lawrence Valley into the water column.

The frequency of deep (>1,000 m) open ocean convection—the process regulating the sinking limb of the AMOC (25)—in the central Labrador Sea and Greenland Sea deep water formation regions responds differently to the three advective pathways we observe from our integrations. Meltwater discharge from the St. Lawrence Valley reduces the frequency of open-ocean deep convection (*Methods*) by only 9% (Table 1). This rather modest impact stems from the fact that the majority of the meltwater lies too far south of the deep convection regions to have any significant impact, whereas any meltwater that advects northward toward the subpolar gyre undergoes rapid horizontal and vertical mixing with the energetic and turbulent Gulf Stream flow. In contrast, favorable circulation dynamics in the Nordic Seas (resulting from the Jan Mayen Current and East Icelandic Current), in concert with instabilities (eddies) in the WGC, allow meltwater discharge from the Mackenzie Valley to rapidly reach the open ocean convection sites. When the CAA is open, the frequency of open-ocean deep convection in the Labrador and Greenland Seas reduces by 28% and 62%, respectively, and by 63% and 77% when the CAA is closed. Only when meltwater is first routed to the Arctic Ocean, via the Mackenzie Valley, is it capable of forming a layer of freshwater, or "freshwater cap," across the subpolar North Atlantic that disrupts open-ocean deep convection (Fig. 3). In addition, only when the CAA is closed is it possible to create a meltwater distribution in the North Atlantic somewhat reminiscent of the starting point for the traditional hosing experiments (Fig. 2*C*).

Changes in the volume of Denmark Strait Overflow Water (DSOW; *Methods*)—the water mass overflowing Denmark Strait that forms the densest component of North Atlantic Deep Water (NADW) (25)—reflect the ability of the northern and eastern meltwater outlets to disrupt open-ocean deep convection (Fig. 4). The largest reduction (–70%) in overflow occurs in response to an Arctic route with the CAA closed. Opening the CAA reduces flow across the sill by 53%, whereas the more modest impact on open-ocean deep convection from meltwater routed down the St. Lawrence Valley reduces transport by 30%.

The changes in NADW transport influence the strength of both the AMOC (Fig. 4) and the northward transport of heat at 26°N—

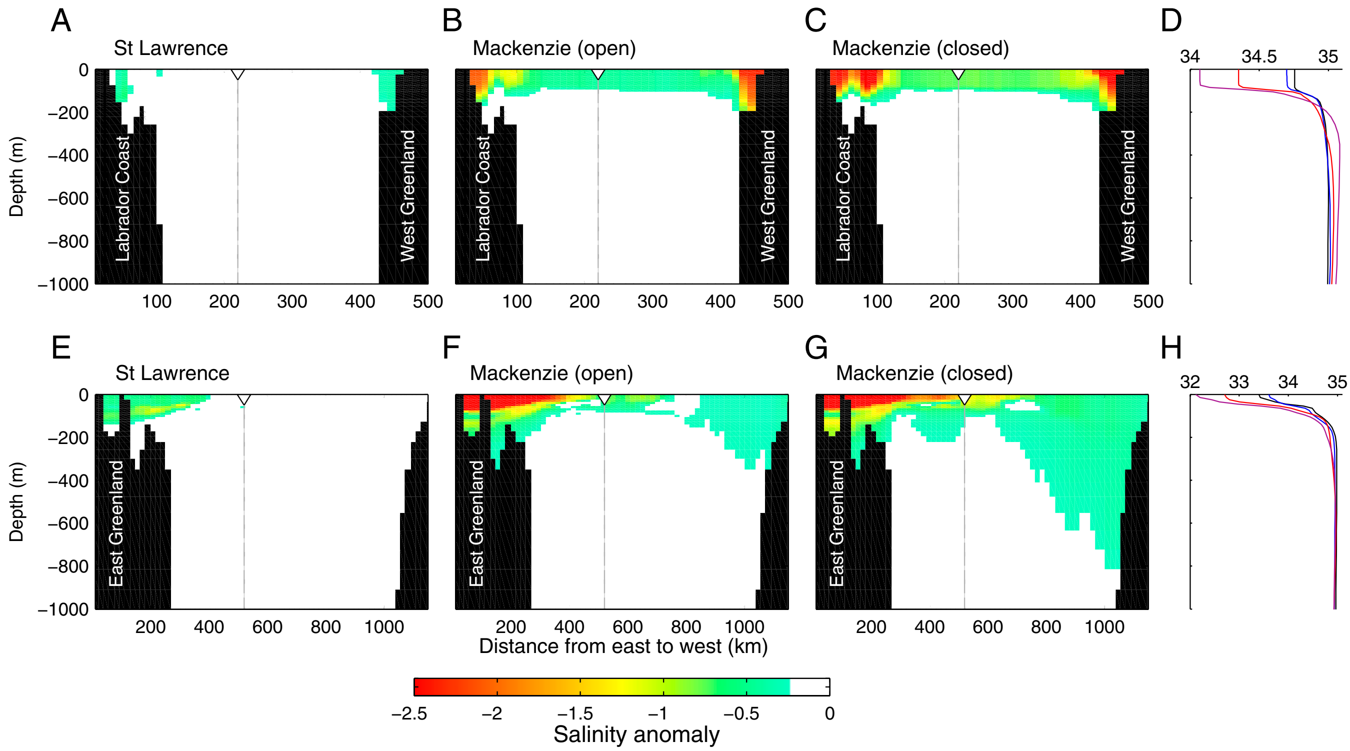

Fig. 3. The distribution of meltwater across the central Labrador and Greenland Seas. The colors (green-red) show the difference in salinity (perturbation minus control) after 10 y of model integration for the (*Upper*) Labrador Sea (World Ocean Circulation Experiment AR7W) and (*Lower*) Greenland Sea (75° N). The vertical salinity profiles (56.5° N, 51° W, Labrador Sea; 75° N, 3° W, Greenland Sea) correspond to sites where open-ocean deep convection has been observed instrumentally (30). The location of these sites are shown by white triangles and vertical lines (*A–C* and *E–G*) and displayed (*D* and *H*) to highlight changes in vertical stratification: control (black), St. Lawrence (blue), Mackenzie (CAA open; red), and Mackenzie (CAA closed; magenta). Only meltwater released from the Mackenzie Valley creates a classic freshwater cap that inhibits open-ocean deep convection. The water column of the central Labrador and Greenland Seas is unaltered by meltwater discharge from the St. Lawrence Valley.

the latitude of the present-day Rapid Climate Change mooring array (26). Meltwater discharge from the St. Lawrence Valley slows the AMOC by 14% (to 14.6 Sv) and reduces northward heat transport by 13% [to 1.09 PW (PW = 10^{15} W)] (Table 1). In contrast, meltwater discharge from the Mackenzie Valley slows the AMOC by 27% (to 12.4 Sv) when the CAA is open, and by 32% (to 11.5 Sv) when the CAA is closed. These changes in overturning are accompanied by similar reductions in the northward transport of heat of 23% (to 0.96 PW) and 29% (to 0.89 PW), respectively.

Discussion

Our high-resolution ocean model integrations shed light on how meltwater discharge into the ocean would reach the open-ocean deep convection regions and weaken the AMOC at the onset of the YD. Contrary to the original hypothesis of Broecker et al. (1), we find that meltwater discharge from the St. Lawrence Valley does not significantly freshen the subpolar gyre or dramatically weaken the AMOC. In contrast to the eastern outlet, meltwater from the Mackenzie Valley disrupts the frequency and depth of open-ocean deep convection in the Greenland and Labrador Seas and significantly weakens both the AMOC and northward transport of heat to the Northern North Atlantic and Arctic Ocean. In agreement with both the recent geological evidence of Murton et al. (13) and the drainage basin modeling of Tarasov and Peltier (8), we conclude that the meltwater trigger for the YD resides in the Arctic.

Our model integrations show that meltwater flowing out of the Gulf of St. Lawrence during the YD had less impact on the strength of the AMOC than a comparable freshwater flux routed through the Arctic Ocean. However, if the open-ocean deep

Table 1. The impact of meltwater from the St. Lawrence River and the Mackenzie River on deep convection and deep ocean circulation

Experiment	LS convection	GS convection	DSOW* (Sv)	AMOC*,† (Sv)	Northward heat transport*,† (PW)
Control	183	225	−3.0	17.0	1.25
Gulf of St. Lawrence	167 (−9%)	204 (−9%)	−2.1 (−30%)	14.6 (−14%)	1.09 (−13%)
Mackenzie (open)	131 (−28%)	85 (−62%)	−1.4 (−53%)	12.4 (−27%)	0.96 (−23%)
Mackenzie (closed)	67 (−63%)	52 (−77%)	−0.9 (−70%)	11.5 (−32%)	0.89 (−29%)

Columns 2 and 3 show the average number of days each year with open ocean deep (>1,000 m) convection in the Labrador Sea (LS) and Greenland Sea (GS). Columns 4–6 show the change in mass transport of DSOW (Denmark Strait Overflow Water), AMOC, and Northward heat transport. Values in parentheses are the percentage reduction from the control integration.

*Mean values for the past 5 y of each integration.

†Calculated at 26° N, the approximate latitude of the modern-day observational Rapid Climate Change mooring array (26).

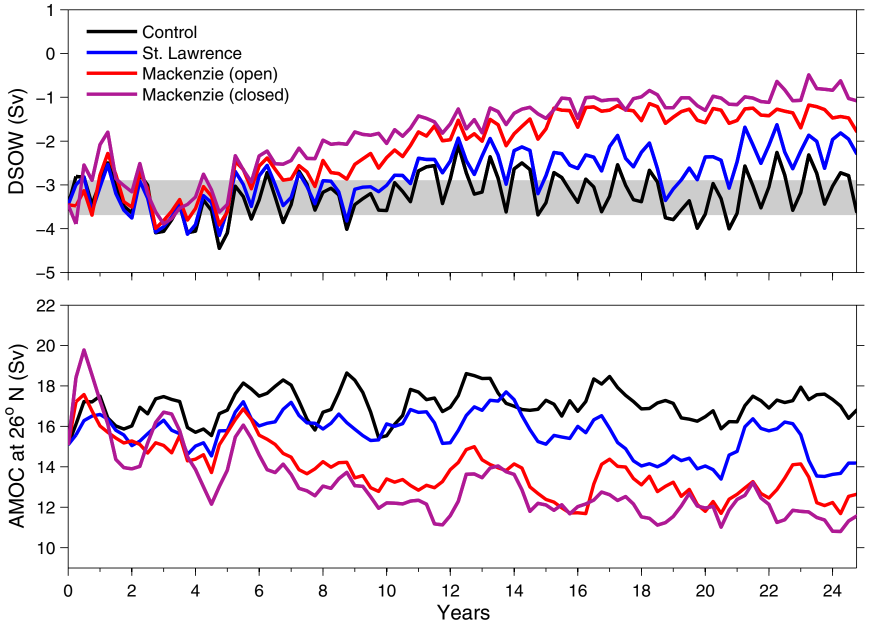

Fig. 4. The mass transport of Denmark Strait Overflow Water and the AMOC. (*Upper*) The mass transport (Sv) at Denmark Strait highlights changes in the southward (shown as negative values) transport of the main water mass contributing to NADW. The modern-day observational range (31) in Denmark Strait Overflow Water (DSOW) transport (–2.9 to –3.68 Sv) is shown by the gray shading. (*Lower*) The strength of the AMOC at 26° N. Note that meltwater discharge from the Mackenzie Valley results in the largest reduction in both DSOW transport and the strength of the AMOC.

convection sites were located considerably farther south in the North Atlantic (compared with present-day conditions) (27), then discharge from an eastern outlet may have had a larger impact on the strength of the AMOC.

During the last deglaciation, the YD manifests itself as one of several prominent cold episodes (8.2-ky event, Preboreal Oscillation [PBO], Intra-Allerød cold period, Older Dryas) that seem to coincide with the abrupt release of meltwater to the ocean from North American glacial lakes (28) (Fig. S3). Intriguingly, there is little direct correlation between the duration and degree of cooling of these cold episodes with the reconstructed volumes of meltwater discharged at their onset. For example, the PBO (~11.3 kya) and the 8.2-ky-event were both centennial in duration and cooled central Greenland by ~2–3 °C, yet reconstructed lake levels suggest ~10 times more meltwater was released into the ocean at the onset of the 8.2-ky event (2, 29). We suggest that part of the difference in the sensitivity of the climate system to meltwater can be explained by the different geographical outlets associated with the two episodes. Geomorphological evidence (2) indicates that the meltwater flood triggering the 8.2-ky event entered the North Atlantic from Hudson Bay (Fig. 1). Recent high-resolution modeling (19) shows that this eastern entry point results in a large fraction of meltwater being transported to the subtropical gyre in the North Atlantic, south of the deep convection regions. In contrast, the meltwater event linked to the PBO appears to have originated from the Mackenzie Valley (29). Our results suggest that this meltwater was efficiently delivered to the open-ocean deep convection regions of the North Atlantic and had a large impact on climate.

Conclusion

Our results show that to understand the sensitivity of the AMOC to meltwater discharge events it is critical to introduce freshwater into models at its source (18–20), rather than spreading it uniformly across the subpolar gyre (50° N to 70° N) of the North Atlantic (15, 17). The same approach should be used to understand the impact of increasing melt rates from Arctic sea ice and the Greenland Ice Sheet on the stability of our modern-day climate. In addition, because ocean boundary currents play such a vital role in delivering meltwater to the open-ocean deep convection regions, coupled climate models such as those used in the Intergovernmental Panel on Climate Change assessments must be integrated at a resolution capable of resolving these and other small-scale features for us to have confidence in climate projections. From a paleoclimate perspective, there is a need to integrate coupled models of the complexity used here for several millennia to fully understand why the YD lasted 1,200 y. Finally, the results presented here point to the Arctic Ocean as a key geographical area for triggering global climate episodes, yet the Arctic Ocean is one of the least understood and sampled oceans on Earth.

Methods

All numerical calculations were performed using MITgcm (14); a coupled ocean sea-ice, free-surface, three-dimensional, primitive equation model. Tracer transport equations are solved using a seventh-order monotonicity preserving advection scheme. There is no explicit horizontal diffusion and vertical mixing follows the K-Profile Parameterization. Our integrations use a cube-sphere grid to permit relatively even grid spacing throughout the domain, with a global horizontal spacing of 18 km and 50 vertical levels ranging in thickness from 10 m to 450 m. The ocean model is coupled to a viscous-plastic rheology sea-ice model. Atmospheric forcing fields were taken from ERA-40 reanalysis data from the European Centre for Medium-range Weather Forecasts. There is no restoring to climatological fields in any of the integrations. Note that the computational limitations of integrating a model of this complexity limit the length of each simulation to 25 y. Mixed layer depths are used to determine the depth of open-ocean deep convection and are defined as the depth at which the density of a grid cell is greater than the surface density by 0.125 $\mathrm{kg \cdot m^{-3}}$. The Greenland and Labrador Sea are defined as 70° N to 80° N, 20° W to 20° E, and 52° N to 65° N, 70° W to 20° W, respectively, where bathymetry exceeds 2,000 m. The transport of Denmark Strait Overflow Water is calculated based on the volumes of water with densities $\geq$1,027.8 $\mathrm{kg \cdot m^{-3}}$ flowing southward at Denmark Strait.

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