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Investigating the impact of Lake Agassiz drainage routes on the 8.2 ka cold event with climate modeling

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Abstract

The 8.2 ka event is the most prominent abrupt climate change in the Holocene and is widely believed to result from catastrophic drainage of proglacial lakes Agassiz and Ojibway (LAO) that routed through the Hudson Bay and the Labrador Sea into the North Atlantic Ocean, and perturbed Atlantic meridional overturning circulation (MOC). One key assumption of this triggering mechanism is that the LAO freshwater drainage was spread over the Labrador Sea. Recent data, however, show no evidence of lowered δ^{18}O values from the open Labrador Sea around 8.2 ka. Instead, negative δ^{18}O anomalies are found close to the east coast of North America, extending as far south as Cape Hatteras, North Carolina, suggesting that the freshwater drainage was probably confined to a long stretch of continental shelf before fully mixing with North Atlantic Ocean water. Here we conduct a sensitivity study that examines the effects of this southerly drainage route on the 8.2 ka event with the ECBilt-CLIO-VECODE model. Hosing experiments of four different routing scenarios, where freshwater was introduced to the Labrador Sea in the northerly route (R1) and to three different locations (Grand Banks – R2, George Bank – R3, and Cape Hatteras – R4) on the southerly route, were performed with 0.45 m sea-level equivalent (SLE), 0.90 m SLE, and 1.35 m SLE of freshwater introduced over 5 years to investigate the routing effects on model responses. The modelling results show that a southerly drainage route is plausible but generally yields reduced climatic consequences in comparison to those of a northerly route. This finding implies that more freshwater would be required for a southerly route than for a northerly route to produce the same climate anomaly.

1 Introduction

The 8.2 ka cold event is the largest abrupt climate change over the past 10 000 years documented in the Greenland ice core records (Alley et al., 1997; Kobashi et al., 2007). This event is characterized by a ~160 year-long cooling (Thomas et al., 2007) accom-

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panied by dry and windy conditions in Greenland (Alley and Ágústsdóttir, 2005). Proxy records from many parts of the world, particularly the circum-North Atlantic region (e.g., Morrill and Jacobsen, 2005; Hughes et al., 2006; Kerschner et al., 2006; Lutz et al., 2007), suggest that this event has been broadly felt in the Northern Hemisphere. This large, abrupt, and widespread cooling event is often interpreted to result from the outburst of proglacial lakes Agassiz and Ojibway (LAO) that flooded the North Atlantic Ocean with freshwater. This would have slowed down Atlantic meridional overturning circulation (MOC), resulting in reduction in polarward heat transport and abrupt cooling (Barber et al., 1999). While far-field anomalies around 8.2 ka may be compounded with the long-term climate variability driven by solar forcing (Rohling and Pälike, 2005), this causal mechanism gains support from both emerging proxy records and climate modeling data. High-resolution records from marine archives document rapid changes in both surface and deep oceans concomitant with the catastrophic drainage of LAO (Ellison et al., 2006; Kleiven et al., 2008). In addition, simulations of freshwater forcing of ocean circulation with climate models have produced climatic responses largely similar to those documented in proxy records (Renssen et al., 2001, 2002; Bauer et al., 2004; LeGrande et al., 2006; Wiersma et al., 2006; Wiersma and Renssen, 2006; LeGrande and Schmidt, 2008).

Previous modeling studies have investigated the impact of the amount and duration of LAO drainage, and the presence/absence of baseline flow on ocean circulation and associated climate change. The previous modeling work assumes that LAO drainage was routed through the Hudson Strait, and then spread over the Labrador Sea before entering the North Atlantic Ocean. However, foraminiferal δ^{18}O data from marine sediment cores from the Labrador Sea do not show the expected depleted δ^{18}O values that appear to occur only on the Labrador shelf, south of the Newfoundland margin, and as far south as Cape Hatteras, North Carolina, between 8 ka and 9 ka (Keigwin et al., 2005) (Fig. 1). In addition, detrital carbonate layers, representing the drainage event, do not appear to spread over the Labrador Sea, but are mainly distributed along the Labrador shelf (Hillaire-Marcel et al., 2007). These data suggest that LAO final drainage may not have spread over the Labrador Sea as often assumed, but perhaps occurred as a buoyant current flowing southeast along the coast reaching as far south as Cape Hatteras before fully mixing with North Atlantic Ocean water. Despite that previous climate modeling has investigated the impact of LAO freshwater drainage on ocean circulation and associated climate change, these studies have focused on LAO drainage that is assumed to spread over the Labrador Sea (i.e., a northerly drainage pathway). The possible effects on the 8.2 ka event of a southerly routing of the LAO drainage, as implied by oxygen-isotope data, has not yet been examined.

The objective of this study is to investigate the routing effects of LAO drainage on ocean circulation and the resulting climate changes around 8.2 ka by introducing freshwater perturbations to both the Labrador Sea and three locations along the southerly drainage route. Investigating the routing effects of LAO drainage around 8.2 ka could contribute to improved understanding of the cause of the 8.2 ka climate event.

2 Methods

2.1 The ECBilt-CLIO-VECODE model

We use the intermediate complexity Earth system model ECBilt-CLIO-VECODE (version 3) to investigate the routing effects of LAO drainage on Atlantic MOC and concomitant climatic responses. ECBilt-CLIO-VECODE is a three-dimensional coupled atmosphere-ocean-vegetation model. The atmospheric component ECBilt is a spectral quasi-geostrophic model that contains three vertical levels and has a T21 ($\sim 5.6^\circ \times 5.6^\circ$) horizontal resolution (Opsteegh et al., 1998). The ocean component CLIO is a primitive-equation, free-surface ocean general circulation model coupled with a thermodynamic-dynamic sea-ice model. CLIO consists of 20 vertically unevenly spaced levels and has a $3^\circ \times 3^\circ$ horizontal resolution (Goosse and Fichefet, 1999). The terrestrial vegetation component VECODE takes into account evolution of vegetation cover that comprises trees, grasses, and desert (Brovkin et al., 2002).

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The utility of this model has been demonstrated in several previous studies, showing that it can reproduce major characteristics of modern climate reasonably well under present-day forcing conditions (Goosse et al., 2001; Renssen et al., 2002). Also, this model has been frequently employed to investigate Holocene climate evolution (e.g., Renssen et al., 2005; Goosse et al., 2005) and abrupt climate changes such as the 8.2 ka event (e.g., Renssen et al., 2001, 2002). In addition, the upgraded version 3 of this model has improved its robustness by allowing deep water formation in not only the Greenland-Iceland-Norwegian (GIN) Sea, but also the Labrador Sea under modern climate conditions. This version of the model has been used to simulate freshwater forcing to ocean circulation and climate change around 8.2 ka (Wiersma et al., 2006). A detailed description of the model can be found at http://www.knmi.nl/onderzk/CKO/ecbilt.html.

Although the ocean component, CLIO, of this model does not have a horizontal resolution sufficient to characterize eddies which are important in mixing of freshwater and ocean water, a recent study demonstrates that responses of the coarse-resolution ECBilt-CLIO-VECODE model are largely similar to those of eddy-permitting resolution models (Spence et al., 2008). The coarse resolution of the model also prevents it from describing in detail the western boundary current, which flows eastward and then southward along the North American coast. This means that the model cannot track freshwater drainage following a southerly route. However, a southerly drainage could be represented by introducing freshwater at a number of locations sequentially along a southerly drainage route. Therefore, despite these limitations, the ECBilt-CLIO-VECODE model can provide important insights into the impacts of routing effects on ocean circulation and climate change.

2.2 Experimental setup and design

Wiersma et al. (2006) examined various freshwater perturbation scenarios using version 3 of the ECBilt-CLIO-VECODE model for the 8.2 ka climate event. The present study takes Wiersma et al.'s (2006) work a step further by investigating freshwater routing effects on ocean circulation and climate changes around 8.2 ka. Therefore, the experimental setup is the same as that of Wiersma et al. (2006) with greenhouse gas concentrations (Raynaud et al., 2000) and orbital parameters (Berger and Loutre, 1991) tuned to represent the conditions at 8.5 ka. Also, a baseline flow of 0.172 Sv is introduced to the Labrador Sea to account for the background Laurentide Ice Sheet melting (Teller et al., 2002). The model with these boundary conditions was run until it reaches quasi-equilibrium in the deepest ocean layer, which is defined by $dT/dt<0.0002^{\circ}\mathrm{C}/100\,\mathrm{yr}$.

To examine LAO routing effects, we perturbed the early Holocene climate system by introducing freshwater over a 5-year period to the Labrador Sea, which represents a northerly routing scenario (Route 1, or R1), and to three other different locations along the southerly drainage route near Grand Banks (R2), Georges Bank (R3), and Cape Hatteras (R4) (Fig. 1). After the 5-year freshwater perturbation, the model run continued for 500 years or more with a baseline flow at the exact same location and rate as for the pre-perturbation state. Such an experimental design that holds both initial and boundary conditions constant permits the evaluation of the sensitivity of the climate system to changes in the location of freshwater perturbations. The model responses to these four freshwater perturbation scenarios are therefore compared to examine the routing effects of LAO drainage on the early Holocene climate.

Wiersma et al. (2006) showed that the volume of freshwater introduced is a decisive factor affecting model responses. We therefore examine the persistency of model responses related to routing effects, if any, by introducing varying amounts of freshwater. Specifically, we designed three sets of experiments with an amount of freshwater introduced of $1.6\times10^{14}\,\mathrm{m}^3$ (or 0.45 m sea-level equivalent, SLE), $3.2\times10^{14}\,\mathrm{m}^3$ (or 0.90 m SLE), and $4.8\times10^{14}\,\mathrm{m}^3$ (or 1.35 m SLE), over a 5-year period, respectively. For a given amount of freshwater introduced, simulations of four different routes (R1, R2, R3, and R4) of freshwater perturbation were performed. The amounts of freshwater used in this study are similar to those of single-, double-, and triple-pulse freshwater used in Wiersma et al. (2006). Also, for comparison purposes, the site where Wiersma

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et al. (2006) introduced their freshwater perturbations is located between our sites R1 and R2 (Fig. 1).

3 Results

3.1 Oceanic responses

The spatial distribution of the freshwater anomalies at the end of the 5-year perturbation clearly shows the sites where the perturbations were introduced (Fig. 2). The center of freshwater anomaly (<18 psu) for the northerly route R1 is more confined than for the southerly routes R2, R3, and R4 (Fig. 2). All freshwater perturbation experiments show distinct model responses that are characterized by marked decreases in the strength of MOC in the North Atlantic Ocean (Fig. 3a), the GIN Sea (Fig. 3b), and northward heat transport in the North Atlantic Ocean (Fig. 3c). The magnitude of decrease in these parameters increases as the freshwater volume increases from 0.45 m SLE, through 0.90 m SLE, to 1.35 m SLE. For instance, the MOC strength of R1 route decreases by 5 Sv, 8 Sv, and 10 Sv for the 0.45 m SLE, 0.90 m SLE, and 1.35 m SLE freshwater perturbation, respectively (Fig. 3a).

Overall, the duration of these anomalies, defined as the departure from the mean minus one standard deviation of the 200-year pre-perturbation values, also appears to increase with the increasing volume of freshwater introduced, though not as pronounced as the trend shown by the amplitudes of these anomalies among these three sets of experiments. For example, the MOC anomalies in the GIN Sea last for about 150 years, 200 years, and 250 years for the 0.45 m SLE, 0.90 m SLE, and 1.35 m SLE freshwater perturbations, respectively (Fig. 3b). Within any one of the three sets of freshwater perturbation experiments, the northerly route R1 always produces the largest anomalies among all four routes (Fig. 3). Overall, durations of the anomalies produced by the R1 route tend to be longer than those produced by R2, R3, and R4 routes. However, there are exceptions. For example, the R4 route in the 1.35 m SLE freshwater perturbation led to a MOC anomaly with a >500 year duration (Fig. 3a). An extended 500 year model run was performed (not shown) to determine the duration of the anomaly, showing that the MOC recovered around year 1000 (i.e., the anomaly lasts for about 100 years longer than those of the other experiments). Since the oceanic responses to different routes in each of three sets of freshwater perturbation experiments show, by and large, similar patterns of variation, we chose one set of experiments, i.e. the 0.90 m SLE perturbation experiments, as a representative set for further detailed examination of routing effects in the rest of this paper, unless stated otherwise.

A comparison of the simulated convection depth in the North Atlantic region for the four routing scenarios reveals that the northerly R1 route caused cessation of all convection activity in the Labrador Sea and the weakest deepwater formation in the GIN seas among all four routes (Fig. 4). For the three southerly routes R2, R3, and R4, the conditions for convective activity in the Labrador Sea and the GIN Sea are overall similar, but the GIN Sea deep convection exhibits more strength than that for the northerly R1 route (Fig. 4).

Freshwater perturbations of all four routes led to expansion of sea ice. The R1 route caused the largest sea-ice expansion covering the entire Labrador Sea by the end of the freshwater perturbation, while the three southerly routing scenarios only led to a slight sea-ice expansion over the Labrador Sea (not shown). Figure 5 shows that routes R1, R2, R3, and R4 led to a maximum sea-ice expansion of 12.7×, 12.2×, 12.1×, and 12.0×10^{12} km^2, respectively. Sea-ice expansion of the R1 route also lasted longer than for the other three routes (Fig. 5). Also, R1 appears to trigger an immediate and rapid sea-ice expansion, while sea-ice expansion for R2, R3, and R4 started about 20 or 30 years after the freshwater perturbation. In addition, it appears that the further south the site is located, the later the initiation of sea-ice expansion occurs (Fig. 5).

3.2 Atmospheric responses

To evaluate the modeled atmospheric response to the perturbation scenarios, we analyzed the simulated air temperature at two locations: the Greenland Summit and the

Ammersee, Central Europe. Both sites have well-established proxy records of the 8.2 ka event (e.g., Alley et al., 1997; Kobashi et al., 2007; von Grafenstein et al., 1998). Surface air temperatures at Greenland Summit (Fig. 6a) and the Ammersee (Fig. 6b) of the four different routing scenarios are compared to assess the routing effects. The maximum modeled temperature drop at Greenland Summit is about 2.5°C, which is comparable to the reconstructed 3.3°C of Kobashi et al. (2007), while simulations for Central Europe exhibit a maximum temperature drop of only about 0.8°C, which is about half of the reconstructed 1.5°C drop for the Ammersee (von Grafenstein et al., 1998). Both at Greenland Summit and in Central Europe, the R1 route leads to the most pronounced temperature anomalies (Fig. 6), as evidenced by its largest amplitude and longest duration among all routing scenarios. The temperature anomalies produced by the three southerly routes display similar patterns of variation with comparable magnitudes at both sites. The temperature change is characterized by a brief warming in response to the freshwater perturbation, followed by a prolonged cooling at Greenland Summit (Fig. 6a). The temperature response in Central Europe shows a brief warming spike for each of the three southerly routes immediately following the freshwater perturbation, but they do not exhibit a notable subsequent cooling (Fig. 6b).

4 Discussion

The emerging oxygen-isotope data from the Labrador Sea and the (north)western North Atlantic Ocean that suggest a southerly rather than an often assumed northerly route of LAO drainage around 8.2 ka, has intrigued us to investigate the routing effects of LAO drainage on ocean circulation and associated climate change. We have performed simulations of four different freshwater forcing scenarios (Fig. 1). R1 represents a northerly routing scenario where freshwater was directly introduced to the Labrador Sea, while R2, R3, and R4 represent southerly routing scenarios with a freshwater perturbation introduced at three different locations along a southerly route inferred from oxygen-isotope data (Fig. 1). We have also examined the persistence of model responses due to routing effects by conducting three sets of experiments with the amount of freshwater of 0.45 m SLE, 0.90 m SLE, and 1.35 m SLE.

The model experiments show that larger freshwater perturbations lead to more pronounced MOC anomalies, characterized by larger amplitudes and longer durations (Fig. 3a). These results corroborate the findings by Wiersma et al. (2006) that the volume of freshwater introduced is the decisive factor in affecting the MOC and corresponding climate anomalies. For a given freshwater perturbation, a northerly route (R1) appears to produce distinctively stronger responses than the three southerly routes (R2, R3, R4). Also, the three southerly routes often yield largely similar anomalies in terms of amplitude and duration, but show a tendency that anomalies become weaker as sites of freshwater perturbation are located farther south. Overall, these two features appear to be persistently present regardless of the exact amount of freshwater introduced (Fig. 3), and are thus considered to be robust. Therefore, these two features are regarded as consequences caused by different routes and are discussed below in detail.

4.1 Comparing model results for northerly vs. southerly routes

The most prominent feature of model responses to the four routes (Fig. 1) is that the northerly route (R1) produces distinctively stronger and often longer anomalies than the southerly routes (R2, R3, and R4). This feature persists in both oceanic (Fig. 3) and atmospheric (Fig. 6) responses to freshwater perturbation of different routes and of varying amounts of freshwater introduced. The distinct difference between the northerly and the southerly routes must be related to the degree to which deepwater convection in the Labrador Sea and the GIN Sea is affected. The convection depth data show a marked difference between the northerly route and the three southerly routing scenarios (Fig. 4). R1 route leads to disappearance of deep convection in the Labrador Sea and significantly subdued deep convection in the GIN Sea. The three southerly routes show stronger and more expanded deepwater formation in the GIN Sea than the R1 route. In comparison to the R1 scenario, some convective activity occurs in the

Labrador Sea, though very weak, in all southerly routes. The strong perturbation to the ocean and atmosphere of the R1 scenario may primarily result from the slowdown of deepwater formation in the Labrador Sea. The salinity in the Labrador Sea dropped from about 35 psu to less than 18 psu for the R1 route and to ∼30 to 33 psu for the three southerly routes by the end of the freshwater perturbation (Fig. 2). The intense freshening prevented deepwater formation in the Labrador Sea and led to pronounced anomalies in the R1 scenario. The southerly routes caused only minor freshening in the Labrador Sea due to dilution and thus their effective forcing to ocean circulation is much smaller. As a result, anomalies produced by southerly routes are weaker than those of the northerly R1 route. The difference in the magnitude of the freshwater forcing between the northerly and southerly routes could also explain the distinct difference in the temperature anomalies at Greenland Summit and in Central Europe (Fig. 6). The stronger forcing in the R1 scenario caused more dramatic and prolonged expansion of sea ice in the Northern Hemisphere than in the three southerly routes (Fig. 5). The weaker effective forcing of the southerly routes is also evidenced by the fact that sea-ice expansion did not occur immediately following the freshwater perturbation, but instead started a few decades later (Fig. 5). This delay effect may indicate the time necessary for freshwater perturbations prescribed in a southerly route to be transmitted to the deepwater formation sites and to cause anomalies in model responses. Since sea ice acts as an insulator of heat flux between ocean and atmosphere, the more expanded sea-ice cover in the R1 scenario could have caused more effective reduction of heat flux from ocean to atmosphere. Together with the increase in surface albedo associated with expanded sea-ice cover, this leads to the more pronounced cooling than those of the southerly routing scenarios (Fig. 6). Different routes probably affected the deepwater convection in the GIN Sea in a similar fashion. R1 route caused stronger anomalies in the GIN Sea than the three southerly routes (Fig. 3b). So the notable decrease in the MOC strength in the GIN Sea could have also contributed to the more pronounced responses of the northerly route R1 than those of the southerly routing scenarios R2 through R4 (Fig. 3b).

4.2 Comparing model results for the three southerly routes

The three southerly routes yield model responses that exhibit many similarities (Figs. 3, 6). While the magnitude and duration of the anomalies are largely comparable, anomalies tend to become weaker in magnitude and shorter in duration as the freshwater perturbation site moves farther south from R2 through R4. This pattern appears in the heat transport data of the 0.90 m SLE perturbations (Fig. 3c) and the MOC data of the GIN Sea in the 0.45 m SLE perturbations (Fig. 3b), but is most evident in the sea-ice data (Fig. 5) that show a decrease in the maximum sea-ice extent and shortening in sea-ice expansion from route R2 through R4 (Fig. 5). In addition, the initiation of the sea-ice expansion appears to occur sequentially from route R2 through R4 (Fig. 5). The observed pattern may arise from the difference in the distance from the freshwater perturbation site to the deepwater formation site in the Labrador Sea. As the location at which freshwater is introduced is moved farther away (southward) from the deepwater formation site in the Labrador Sea, the effective freshwater forcing and the corresponding impacts on deepwater convection in the Labrador Sea weaken.

4.3 Implications for the amount of LAO freshwater drainage

The modeling results suggest that a southerly route is feasible and can explain the pattern of δ^{18}O data from the Labrador Sea and its vicinity. Since a southerly route produces a weaker perturbation to the climate system than does a northerly route, this would imply that more freshwater would be required for a southerly route than a northerly routing scenario in order to produce a climatic anomaly similar to that of the 8.2 ka event.

4.4 Limitation of this study

One important assumption in our modeling experiments is that 100% of the freshwater drained from the Hudson Bay was transported to the four respective sites of release

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and that there was no mixing between freshwater and ocean water along the way. In reality, dynamic mixing of freshwater and ocean water could have occurred during transport. Since the ECBilt-CLIO-VECODE model has a coarse spatial resolution (3°×3°) of the ocean component, it is not possible to simulate the detailed dynamic mixing process of freshwater and ocean water. Spence et al. (2008) investigated the sensitivity of the responses to a coarse spatial resolution model and an eddy-permitting resolution model for the 8.2 ka event, and showed that responses of two models of coarse and fine spatial resolution are not significantly different. Therefore, the differential climatic responses we observe in our modeling experiments, particularly the distinctly different responses between the northerly R1 route and the three southerly routes, represent impacts due to different routing scenarios. Future work should focus on improving the spatial resolution of the climate model to adequately describe the topography of continental slopes along the drainage route and to characterize the dynamic dissipation of freshwater into the North Atlantic Ocean. This line of research will further refine our understanding of effective freshwater forcing to ocean circulation for different routes, especially the three southerly routing scenarios. Furthermore, additional detailed paleoceanographic proxy records from the Labrador Sea and northwestern North Atlantic Ocean are needed to provide further constraints on the freshwater drainage pathway.

5 Summary and conclusions

We have simulated four different routing scenarios of LAO drainage around 8.2 ka, with varying amounts of freshwater perturbation to examine the routing effects on climatic responses of freshwater perturbations to oceanic and atmospheric circulation. The modeling results suggest that changes in drainage routes could result in significantly different climatic responses and a southerly route of LAO freshwater drainage as suggested by oxygen-isotope data may be plausible. Overall, the modeling results show that a southerly routing scenario would lead to a weaker climatic anomaly than a northerly routing scenario.

In addition, our modeling results could provide insight into estimating the amount of freshwater drainage associated with the 8.2 ka event. A southerly route would require more freshwater drainage than a northerly route in order to produce a similar climatic anomaly. Future research should focus on improving the spatial resolution of the climate model, incorporating dynamic mixing of freshwater and ocean water during the catastrophic freshwater drainage event, and collecting detailed paleocoeangraphic proxy records to further constrain the freshwater drainage pathway.

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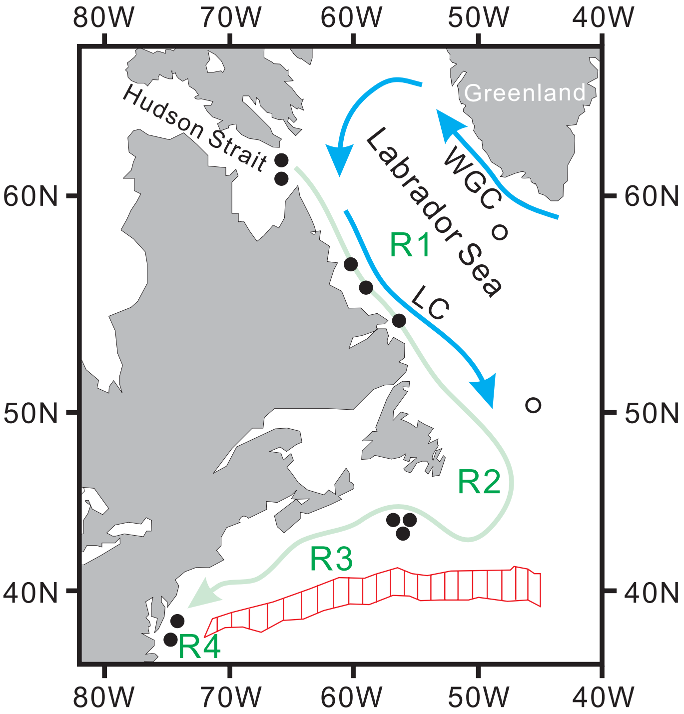

Fig. 1. A map showing schematic circulation of surface currents together with the locations of high-resolution records of Holocene climate change in the northern North Atlantic Ocean (after Keigwin et al., 2005). Dots represent locations where low δ^{18}O between about 8 and 9 ka was documented. Open circles represent sites where no δ^{18}O anomalies are observed. Sites are from Keigwin et al. (2005) and Hillaire-Marcel et al. (1994). The northern boundary of the Gulf Stream (hatched area, the average position) is shown in red. Major cold currents are shown in dark blue. WGC = West Greenland, LC = Labrador Current; The possible route of the freshwater drainage during the 8.2 ka event is shown in light blue. R1, R2, R3, R4 = the location(s) where freshwater was introduced for the experiments.

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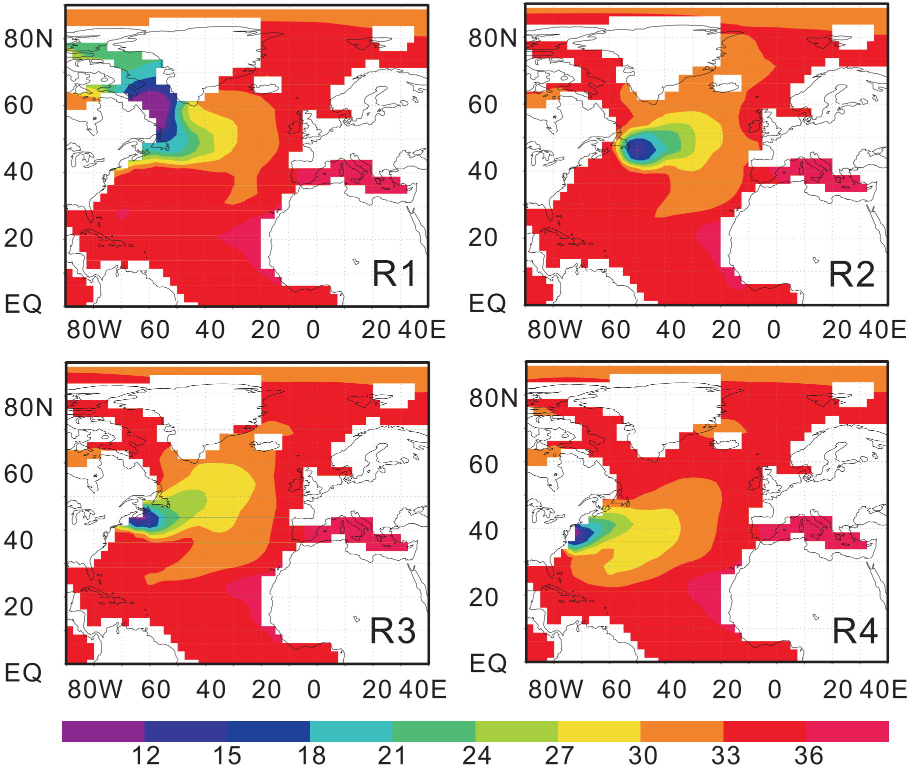

Fig. 2. The sea surface salinity (psu) at the end of the 5-yr freshwater perturbation showing the locations where freshwater was introduced. Graphs show results produced by a 0.9 m sea-level equivalent (SLE) freshwater perturbation for four routing scenarios.

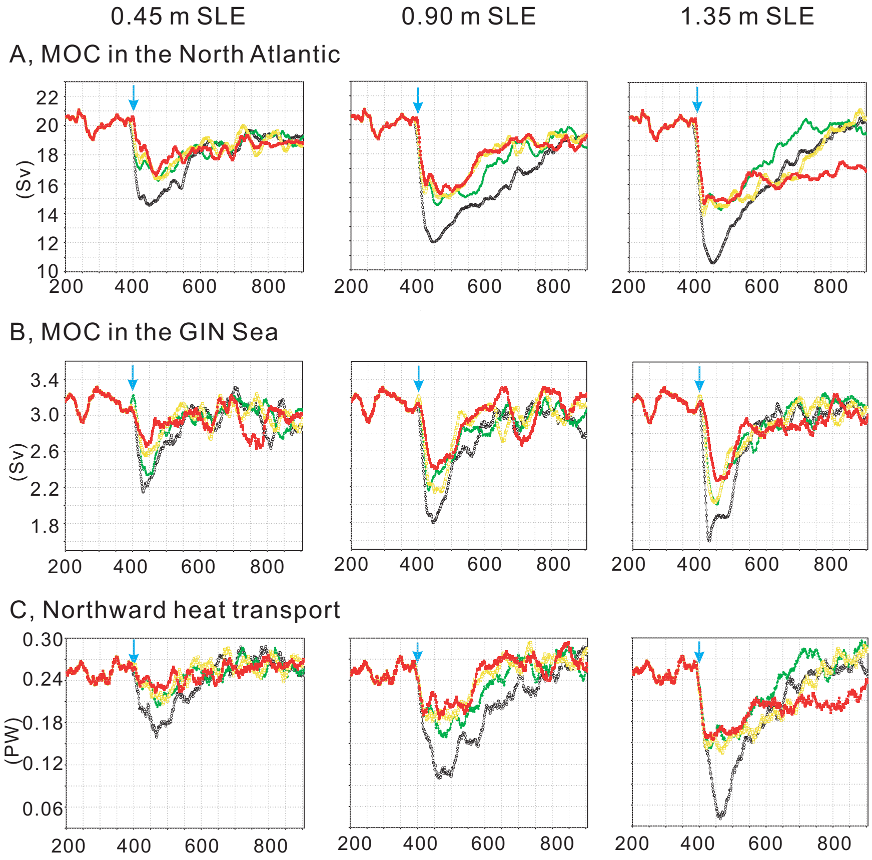

Fig. 3. Time series of meridional overturning circulation (MOC) (Sv) in the North Atlantic **(A)** and the GIN Sea **(B)**, and northward heat transport in the North Atlantic Ocean **(C)**. White=R1; Green=R2; Yellow=R3; Red=R4. Left, middle, right columns are results of 0.45 m SLE, 0.90 m SLE, and 1.35 m SLE freshwater perturbation, respectively. Arrows mark the time when freshwater perturbation is introduced.

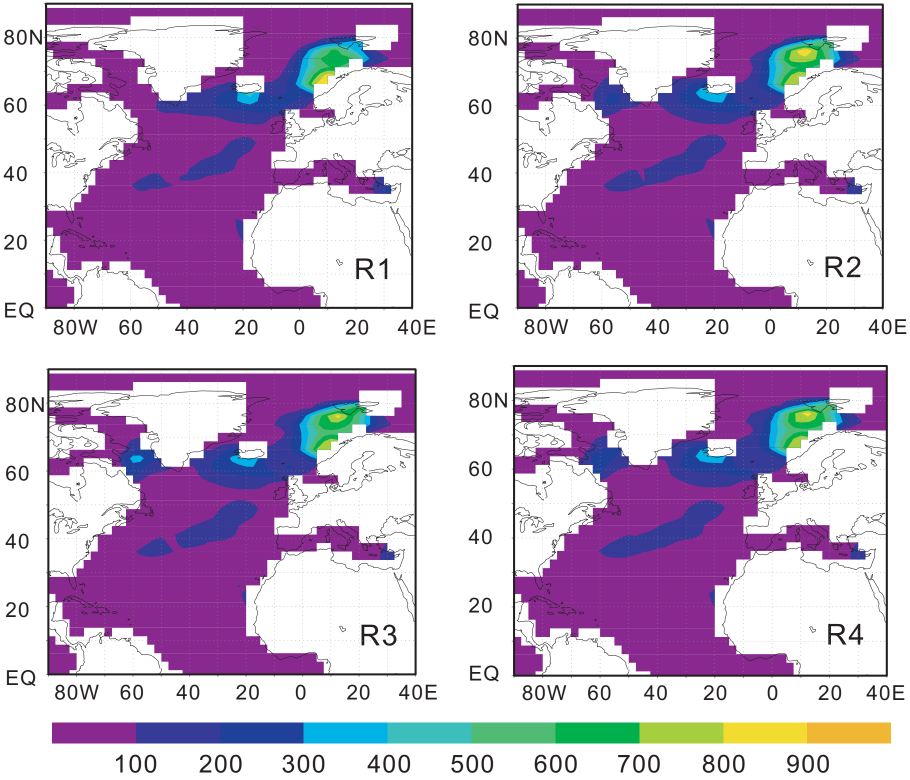

Fig. 4. The mean convection depth in February over 80 years following the freshwater perturbation for the northerly routing (R1, Fig. 1) and southerly routing (R2, R3, R4, Fig. 1) scenarios. The amount of freshwater introduced is 0.90 m SLE.

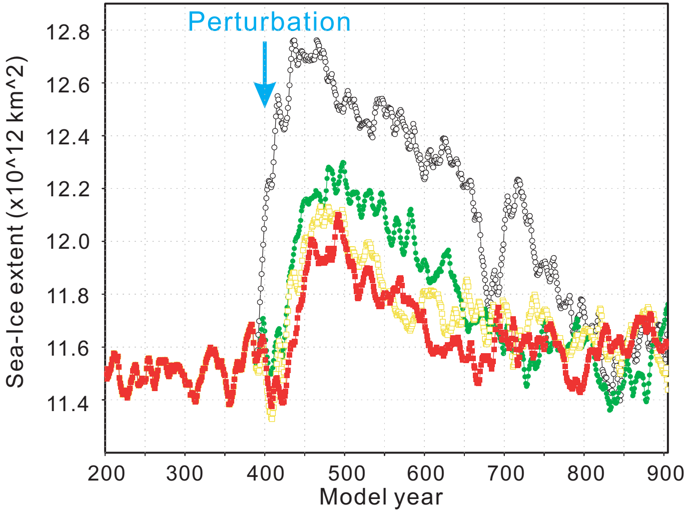

Fig. 5. Changes in sea-ice extent in the Northern Hemisphere after the freshwater perturbations for the northerly routing R1 (black) and southerly routing R2 (green), R3 (yellow), R4 (red) scenarios.

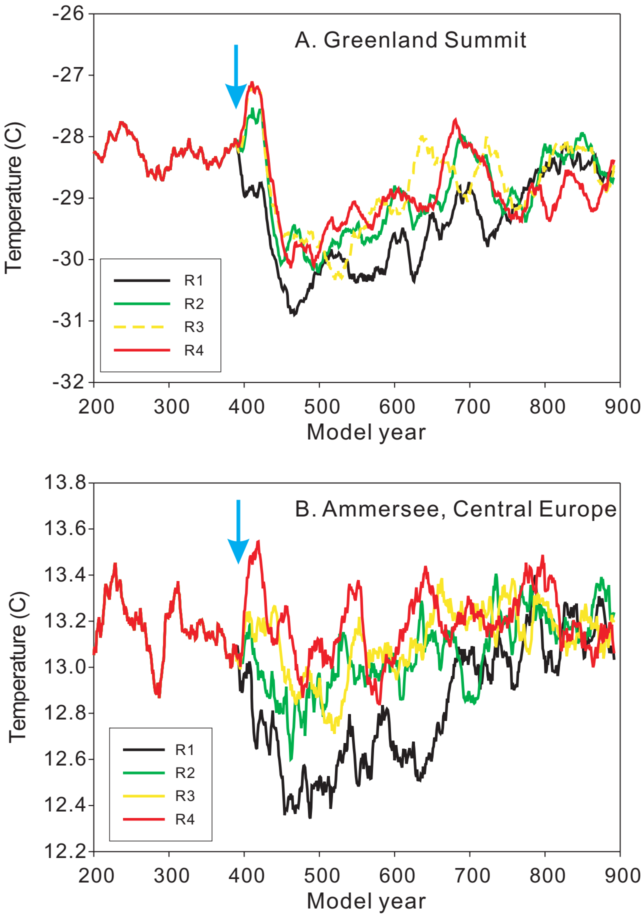

Fig. 6. Time series of the 25-year running mean temperatures at Greenland Summit **(A)** and Ammersee in Central Europe **(B)** for freshwater perturbations of the northerly (R1) and southerly (R2, R3, R4) routing scenarios.