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The 8.2 ka event: Abrupt transition of the subpolar gyre toward a modern North Atlantic circulation

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[1] Climate model simulations of the 8.2 ka event show an abrupt strengthening of the Atlantic subpolar gyre that allows us to connect two major but apparently contradictory climate events of the early Holocene: the freshwater outburst from proglacial lakes and the onset of Labrador Sea water formation. The 8.2 ka event is the largest climatic signal of our present interglacial with a widespread cooling in the North Atlantic region about 8200 years before present. It coincides with a meltwater outburst from North American proglacial lakes that is believed to have weakened the Atlantic meridional overturning circulation and northward heat transport, followed by a recovery of the deep ocean circulation and rising temperatures after a few centuries. Marine proxy data, however, date the onset of deep water formation in Labrador Sea to the same time. The subsequent strengthening of the slope current system created a regional signal recorded as an abrupt and persistent surface temperature decrease. Although similarities in timing are compelling, a mechanism to reconcile these apparently contradictory events was missing. Our simulations show that an abrupt and persistent strengthening of the Atlantic subpolar gyre provides a plausible explanation. The intense freshwater pulse triggered a transition of the gyre circulation into a different mode of operation, stabilized by internal feedbacks and persistent after the cessation of the perturbation. As a direct consequence, deep water formation around its center intensifies. This corresponds to the modern flow regime and stabilizes the meridional overturning circulation, possibly contributing to the Holocene's climatic stability.

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1. Introduction

[2] During the relatively stable conditions of our present interglacial, the 8.2 ka event is the largest climatic signal with a widespread cooling in the North Atlantic region about 8200 years before present. It coincides with a meltwater outburst from North American proglacial lakes [*Alley et al.*, 1997; *Alley and Ágústsdóttir*, 2005, and references therein]. In current understanding, this caused a weakening of the Atlantic meridional overturning circulation (AMOC) and a subsequent reduction in northward heat transport, followed by a recovery of the deep ocean circulation and rising temperatures after a few centuries [*Bauer et al.*, 2004; *Hall et al.*, 2004; *Ellison et al.*, 2006; *Wiersma et al.*, 2006; *Kleiven et al.*, 2008].

[3] This two-dimensional explanation, however, is not able to explain a number of marine paleo-records that clearly call for a three-dimensional mechanism. An abrupt but persistent surface temperature decrease was reported from the western North Atlantic at the time of the 8.2 ka event (Figure 1) [*Solignac et al.*, 2004; *de Vernal and Hillaire-Marcel*, 2006; *Sachs*, 2007]. It has been suggested to be associated with the onset of deep water formation in Labrador Sea and a subsequent strengthening of the slope current system, the western branch of the subpolar gyre (SPG) [*Hillaire-Marcel et al.*, 2001; *Sachs*, 2007]. Proxy data from Reykjanes Ridge shows a similarly abrupt and persistent warming which provides evidence for an enhanced Irminger Current (Figure 1) [*Andersen et al.*, 2004; *Came et al.*, 2007]. This is the northeastern branch of the SPG and thus corroborates the hypothesis of a stronger gyre and enhanced convection in its center.

[4] The concurrence of these two events raises the question of how convection can increase at the time of the most severe freshwater flood of the past 10,000 years. We argue, based on coupled climate model experiments, that this is no contradiction but that a causal relationship connects the two events. A change in the density structure is found to provide positive feedbacks leading to a permanent strengthening of the SPG and convection. The impact of baroclinic adjustments on the SPG strength is well documented [*Eden and Willebrand*, 2001; *Häkkinen and Rhines*, 2004; *Hátún et al.*, 2005; *Treguier et al.*, 2005; *Levermann and Born*, 2007; *Born et al.*, 2009; *Lohmann et al.*, 2009; *Born et al.*, 2010; *Montoya et al.*, 2010] and this study aims to apply this physical understanding to data from the geological record.

2. Model Description

[5] To investigate the role of the SPG during the 8.2 ka event we make use of the coupled climate model CLIMBER-3α, which comprises atmosphere and sea ice components and the oceanic general circulation model MOM-3 (*Montoya et al.* [2005] and auxiliary material).[1] The oceanic horizontal resolution is 3.75° × 3.75° with 24 unevenly spaced vertical layers. Simplified atmosphere dynamics are solved on a coarse numerical grid (7.5° in latitude and 22.5° in longitude).

[6] Due to the coarse resolution of the model, the SPG and deep water formation in its center are shifted eastward and simulated boundary currents are relatively broad (Figure 2). A second deep water formation region is found in the Nordic seas. Despite shortcomings, the interaction between gyre advection, convection in its center and eddy transport in between, as well as the communication of deep water masses across the deepest passages of the Greenland-Scotland ridge, compares well to higher-resolution models [*Spall*, 2005; A. Born et al., Late Eemian warming in the Nordic seas as seen in proxy data and climate models, submitted to *Paleoceanography*, 2010]. For additional information we refer to sensitivity studies with glacial [*Montoya et al.*, 2010] and present-day boundary conditions [*Mignot et al.*, 2006] as well as under global warming [*Levermann et al.*, 2007].

[7] For the present study, the model was initialized with climatological hydrography [*Levitus*, 1982] and orbital parameters for 8,200 years before present [*Berger*, 1978]. Atmospheric CO_2 concentration was set to 260 ppm [*Raynaud et al.*, 2000]. The continental watershed over North America was shifted to the west and south in order to take into account changes in surface gradient due to the isostatic depression of glacial ice sheets. After the model was run into equilibrium over 2700 years, the simulated SPG exhibits a stable but weak volume transport of 19.5 Sv (1 Sv = 10^6 m^3 s^{-1}). In order to simulate the lake drainage, $160 \cdot 10^{12}$ m^3 of freshwater were added to the surface of the Labrador Sea coast during a period of two years, west of the deep convection region. This value is equivalent to a 2 year volume

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GC003024.

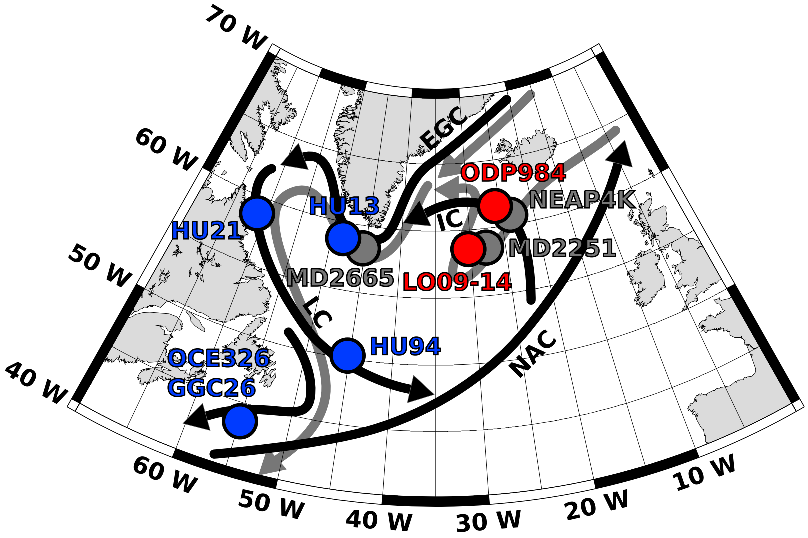

Figure 1. Map of the subpolar North Atlantic showing the location of core sites and of major ocean currents mentioned in the text. Blue dots denote cores that show an abrupt and persistent cooling after 8 ka before present; warming is reported from the Reykjanes Ridge and marked red. Grey dots show where the 8.2 ka event is evident as a temporal reduction in deep current flow speed. Black arrows illustrate the surface currents (IC, Irminger Current; EGC, East Greenland Current; LC, Labrador Current; NAC, North Atlantic Current); grey arrows illustrate the Deep Western Boundary Current. For a list of full core names and references, please refer to Table S1 in Text S1.

flux of 2.6 Sv, based on a recent estimate of the lake volume [*Leverington et al.*, 2002], and has been used in previous model studies [*Bauer et al.*, 2004; *LeGrande et al.*, 2006; *Wiersma et al.*, 2006]. For diagnostic purposes, a passive tracer was released simultaneously with the freshwater flux at the same location in order to track advection of the perturbation. This tracer does not influence the circulation. We define the strength of the subpolar gyre as the local minimum of the depth integrated stream function. For the cyclonic circulation of the SPG, this stream function is negative (Figure 2).

3. Model Results and Interpretation of Proxy Data

[8] In response to the meltwater release, the SPG switches into a significantly stronger mode with 29 Sv volume transport (Figures 2 and 3a). This represents a strengthening of about 50% and the stronger circulation is within the uncertainty of present-day observations [*Bacon*, 1997; *Read*, 2001]. Further integration shows that this stronger state is stable and not only a temporary response to the freshwater pulse.

[9] The abrupt transition is due to two positive feedbacks inherent to the SPG [*Levermann and Born*, 2007]. First, a stronger SPG transports less tropical saline water into the Nordic seas but accumulates these in the subpolar North Atlantic, making upper water masses in the center of the SPG more saline (Figures S7–S9 in Text S1). This is consistent with previous conclusions which are based on simulations with a high-resolution ocean general circulation model and confirmed by observations [*Hátún et al.*, 2005; *Lohmann et al.*, 2009]. Increased surface salinity enhances deep convection, cooling the deep water column. Besides, a stronger SPG results in enhanced outcropping of isopycnals

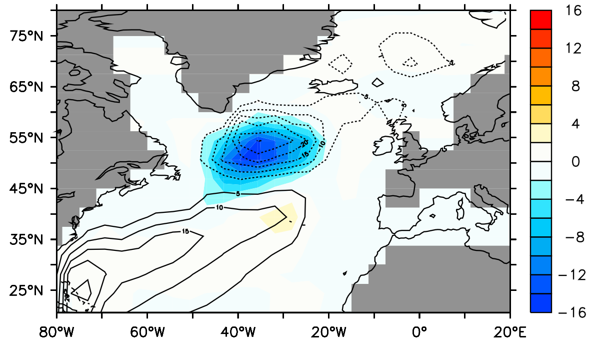

Figure 2. Colors indicate anomaly of the vertically integrated stream function, last 50 years of the perturbed simulation minus last 50 years before the meltwater pulse. Contours indicate vertically integrated stream function for the last 50 years of the simulation. For the cyclonic circulation of the SPG, the negative anomaly represents a strengthening. Outside the subpolar North Atlantic, currents are virtually unchanged.

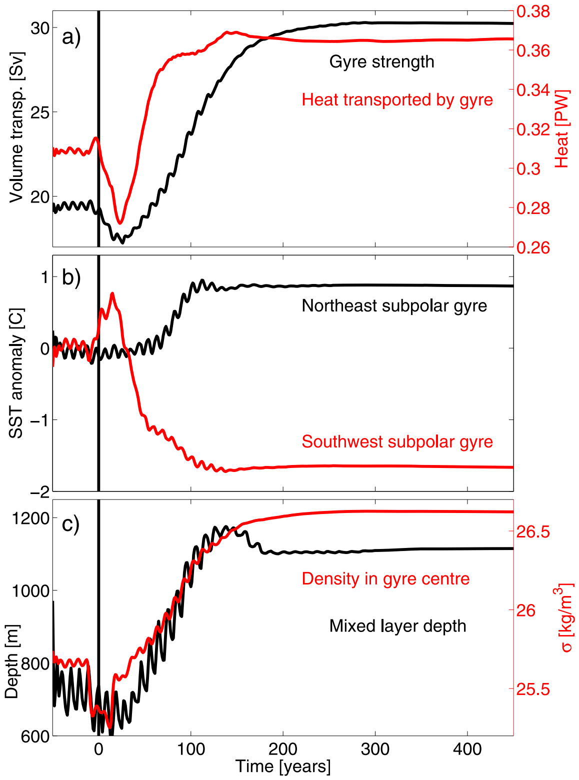

Figure 3. Temporal evolution of key quantities of the transition toward a stronger SPG during the 8.2 ka event. The vertical line indicates the timing of the lake Agassiz drainage; data are filtered with a 25 year running mean. (a) Volume and heat transport of the SPG, (b) sea surface temperature in the northeastern (black) and southwestern (red) subpolar region, and (c) maximum winter mixed layer depth in the center of the SPG and surface density in the center of the SPG (see Figure S7 in Text S1). The stronger heat transport leads to a warming of the northeastern gyre region while the southwestern part cools rapidly. Surface density and mixed layer depth increase simultaneously.

and hence a more efficient removal of heat from the gyre's center by isopycnal mixing. Both effects, salt accumulation and removal of heat, increase the core density of the gyre compared to the relatively light exterior, sea surface drops and the corresponding geostrophic response strengthens the cyclonic SPG circulation.

[10] In addition to these self-sustaining internal feedbacks, there exists an interaction with the flow over the Greenland-Scotland ridge. The meltwater perturbation reduces sinking in the Nordic seas and therewith the supply of dense overflow waters to the northern rim of the SPG. Consequently, the outer rim of the gyre gets lighter and the gyre slightly intensifies. This triggers the two internal feedbacks mentioned above and yields the stronger SPG state (Figure S1 in Text S1). Elsewhere, we have shown that a short reduction of dense deep outflow from the Nordic seas is sufficient to trigger the transition (≥25 years [*Levermann and Born*, 2007]) and that the described internal feedbacks dominate the dynamics. Changes in wind stress are small and do not show a consistent pattern (Figure S6 in Text S1). This is plausible because the freshwater flood does not impact wind patterns directly. Moreover, the coarse resolution of the atmosphere component might underestimate regional variations. Thus, the changes in wind stress seen after the transition are likely due to local changes in sea ice as suggested also by the irregular pattern. The mechanism of transition is robust to prescribed wind forcing and with respect to model setup and experimental design (see auxiliary material).

[11] Considering this change in surface circulation allows us to combine a number of proxy records into a consistent picture of the 8.2 ka event. Recent work found strong evidence for a reduction of dense water supply from the Nordic seas due to the lake Agassiz drainage [*Hall et al.*, 2004; *Ellison et al.*, 2006; *Kleiven et al.*, 2008]. However, proxy data suggests that the meltwater signal did not reach the convection region at the center of the Labrador Sea but was exported along the shelf in the Labrador Current [*Keigwin et al.*, 2005; *Hillaire-Marcel et al.*, 2007]. From there a large portion moved northeastward and was diluted by mixing with water of the North Atlantic Current before reaching the Nordic seas and causing a moderate reduction in convection there. Our model reproduces this path qualitatively. 30 years after the lake drainage, highest concentrations of meltwater are found in the Nordic seas where 25% of the meltwater pulse has been advected to (Figure 4).

[12] After the transition, the stronger SPG circulation intensifies oceanic heat transport (Figure 3a). More warm tropical water reaches the northern SPG while more cold water is advected toward the west and south. This results in a sea surface temperature (SST) dipole (Figure S7 in Text S1). The southwestern SPG region cools abruptly (Figure 3b, red) while rapid warming is seen in the northeastern SPG region (Figure 3b, black).

[13] An abrupt and persistent SST decrease coeval with the lake drainage has indeed been reported from dinoflagellate cysts and alkenones for many locations throughout Labrador Sea and downstream Labrador Current south of Newfoundland [*Solignac et al.*, 2004; *de Vernal and Hillaire-Marcel*, 2006; *Sachs*, 2007]. Consistent with our simulations this

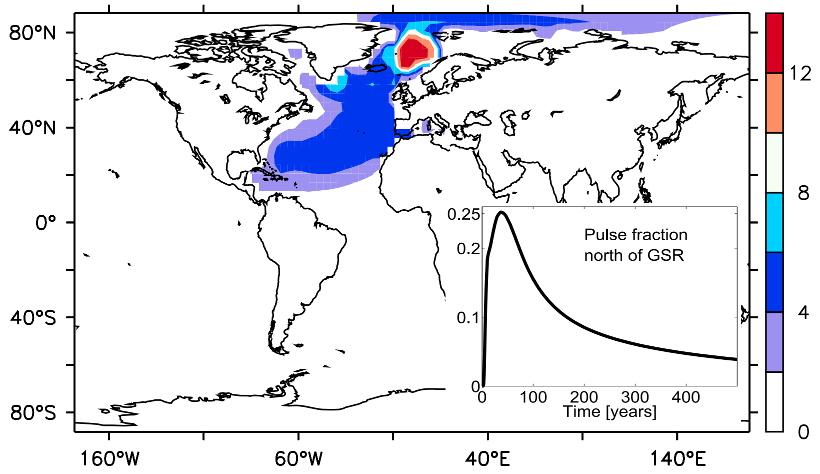

Figure 4. Distribution of the meltwater pulse 30 years after its release into the Labrador Sea, integrated over depth (in m). Highest concentrations are found in the Nordic seas. Inset shows the fraction of the pulse in the Nordic seas and the Arctic Ocean. After approximately 30 years, 25% of the meltwater is advected north of the Greenland-Scotland ridge, followed by a decline as it is diluted globally.

data indicates a drastic reorganization of the slope current system. No persistent cooling is seen in foraminiferal data from Eirik Drift in the northern Labrador Sea, probably because of its location too far offshore to record changes in the coastal current [*Kleiven et al.*, 2008]. The warming signal on the eastern side of the gyre is not easily detected in proxy records because the strengthening of the surface circulation also changed the position of frontal systems. Thus, the strengthening of the SPG is recorded as a subsurface cooling inferred from foraminifera at a relatively eastern location [*Thornalley et al.*, 2009]. However, approximately 400 km further west on Reykjanes Ridge, where currents are more constrained by topography, an increase and stabilization of surface temperatures reconstructed using diatoms, foraminiferal δ^{18}O and Mg/Ca data has been associated with an intensification of the Irminger Current, the northern limb of the SPG (Figure 1) [*Andersen et al.*, 2004; *Came et al.*, 2007].

[14] Further support for a transition toward a stronger SPG following the 8.2 ka event comes from increased sea surface salinities throughout the subpolar region that started similarly abrupt as the temperature changes and were equally persistent, both in our model experiments (Figures S7–S9 in Text S1) and proxy data [*Solignac et al.*, 2004; *de Vernal and Hillaire-Marcel*, 2006; *Hillaire-Marcel et al.*, 2007; *Came et al.*, 2007]. The cooling of western slope waters can thus not be attributed to more intense transport of cold and fresh Arctic waters through the East Greenland Current. Their upstream source must be the relatively saline Irminger Current which suggests a SPG intensification. A sudden increase in advection of Atlantic water into Labrador Sea has also been concluded from diatoms, fossil shell data and foraminiferal assemblages at several locations along the Greenland west coast [*Donner and Jungner*, 1975; *Lloyd et al.*, 2005; *Ren et al.*, 2009]. The intensification of westward salt transport and the eastward movement of the subpolar front with a stronger SPG results in a freshening of inflow into the Nordic seas (Figure S7 in Text S1), consistent with paleo-observations [*Thornalley et al.*, 2009] and present-day instrumental records [*Hátún et al.*, 2005]. Salt accumulation in the center of a anomalously strong SPG has been shown in a higher-resolution model [*Lohmann et al.*, 2009].

[15] Proxy data of Labrador Sea convection furthermore supports a significant reorganization of the surface circulation. In our simulations, enhanced surface salinity together with subsurface cooling in the center of the SPG results in a density increase and a subsequent intensification of convection south of the Greenland-Scotland ridge (Figure 3c). These results match well with existing data of the geological record. Little or no Labrador Sea Water was produced in the early Holocene and formation intensified not long after the meltwater outburst [*Hillaire-Marcel et al.*, 2001, 2007]. Isotopic changes in Labrador Sea sediments show a persistent reorganization of the deep current system after 8,000 years before present [*Fagel et al.*, 2004] with deeper Labrador Sea Water found in Pa/Th data [*Gherardi et al.*, 2009] and a permanent reduction of deep water formed in the Nordic seas

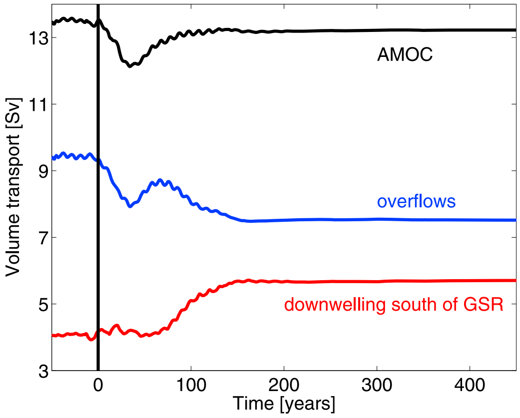

Figure 5. The Atlantic Meridional Overturning Circulation (AMOC), decomposed into deep water contributions from sinking in the Nordic seas (blue) and south of the Greenland-Scotland ridge (red). The vertical line indicates the timing of the lake Agassiz drainage, and a 25 year running mean filter is applied. The AMOC weakens abruptly in response to the freshwater event and recovers gradually over approximately 100 years. While the initial weakening is caused by the reduction of deep water supply from the Nordic seas, the recovery is due to a delayed intensification of Labrador Sea deep water formation. Both Nordic seas and Labrador Sea downwelling change significantly and persistently.

recorded in benthic δ^{13}C data [*Evans et al.*, 2007]. This points toward a persistent reorganization of both the horizontal surface and the deep meridional circulation, as simulated here.

[16] In contrast to significant changes in SPG strength (47%), the AMOC weakens by just 1.5 Sv (11%) in response to the meltwater pulse, significantly less than the 30%–50% reduction reported from previous model studies [*Bauer et al.*, 2004; *Wiersma et al.*, 2006; *LeGrande et al.*, 2006] (Figure 5). The strong response in earlier simulations might be due to the application of the meltwater pulse directly on the Labrador Sea convection region with dramatic consequences for SPG and AMOC. Such a freshwater perturbation leads to a reduction of convection in the Labrador Sea contradicting the paleorecord that shows the intensification of convection in this region. Moreover, this scenario removes a significant fraction of the freshwater pulse from the surface, inconsistent with proxy data indicating its advection in the Labrador Current. Hence, a smaller fraction is advected into the Nordic seas which is crucial to initiate the mechanism amplifying the SPG as discussed above (see auxiliary material for further discussion). The initial AMOC weakening in our simulation is followed by a rapid recovery over approximately 100 years and then a more gradual increase. The decomposition into deep water formation regions shows that the initial weakening is due to reduced sinking in the Nordic seas, reaching its minimum after 150 years. The recovery and weak overall reduction is due to an increase in deep water formation south of the Greenland-Scotland ridge with a time lag of approximately 50 years (Figures 5 and 3c).

[17] A distinctive reduction in deep current flow speeds, probably delayed by at least several decades, is reported from the Greenland-Scotland ridge overflows and off the southern tip of Greenland (Figure 1) [*Hall et al.*, 2004; *Ellison et al.*, 2006; *Kleiven et al.*, 2008]. This is upstream from where Labrador Sea Water joins the Deep Western Boundary Current, the southward flowing branch of the AMOC. Further south in the North Atlantic, the reduction of northern source deep waters is minor for the 8.2 ka event if recorded at all [*Keigwin and Boyle*, 2000; *Oppo et al.*, 2003; *Keigwin et al.*, 2005]. The onset of Labrador Sea Water formation following the meltwater pulse might explain this discrepancy.

4. Summary and Conclusions

[18] Expanding previous studies that focused on the AMOC response, i.e., changes in the meridional circulation, to the lake Agassiz drainage, we propose that many observed but hitherto unexplained abrupt changes and discrepancies require taking into account a reorganization of the horizontal circulation. The most striking result is the persistent strengthening of the SPG in response to the short freshwater pulse. The transition between the two circulation patterns is triggered by an external positive feedback and stabilized by two positive feedback mechanisms within the SPG.

[19] While our results do not contradict an abrupt and considerable AMOC reduction in response to the lake Agassiz drainage, it might have been relatively short lived and weaker than suggested by previous simulations for two reasons: (1) The freshwater flood had the biggest impact not in the Labrador Sea but primarily affected deep water formation in the Nordic seas after mixing in the North Atlantic Current (Figure 4) and (2) this deep water reduction was partly compensated by enhanced sinking in the Labrador Sea (Figures 3c and 5). The latter mechanism has already been observed in models and data on time scales of several millennia [*Renssen et al.*, 2005; *Solignac et al.*, 2004].

[20] In our model the reorganization of the SPG surface circulation and subsequent changes in heat and salt advection provide the precondition for a more intense Labrador Sea convection and stabilize it. It has been suggested that this circulation mode is a unique feature of the Holocene, with Labrador Sea Water probably missing in the warmer climate of the last interglacial [*Hillaire-Marcel et al.*, 2001] and implications for the stability of the AMOC by the end of this century. Our results might provide the base for a future investigations of these hypotheses.

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