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Notes

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ABSTRACT

During the last deglaciation (ca. 19–6.5 ka), increased freshwater discharge to the North Atlantic likely caused reductions in Atlantic meridional overturning circulation (AMOC) strength. However, the locations and rates of freshwater discharge are not well constrained, particularly those during the centennial-scale climate oscillations of the Bølling-Allerød warm periods (ca. 14.6–12.9 ka). Here we reconstruct the salinity-dependent $\delta^{18}O_{sw}$ (sw, seawater) adjacent to the eastern outlets of North America, using paired Mg/Ca and $\delta^{18}O$ records on planktonic foraminifera, to investigate whether increased discharge to the North Atlantic caused reductions in AMOC during the Bølling-Allerød and earlier periods of deglaciation. In general, $\delta^{18}O_{sw}$ decreased and inferred freshwater discharge increased during periods of reduced AMOC. During the Bølling-Allerød, $\delta^{18}O_{sw}$ decreases coincided with three reductions in AMOC strength ca. 14.1, 13.8, and 13.3 ka. Freshwater discharge modeling suggests that discharge increases of 0.03–0.05 Sverdrups (10^6 m^3 s^{-1}) would explain these $\delta^{18}O_{sw}$ decreases, which were sufficient to force reductions in AMOC strength. Concurrent changes in North Atlantic temperature, and subtropical and tropical atmospheric circulation and precipitation imply that small variations in the North Atlantic hydrologic system may have significant impacts on Northern Hemisphere climate.

INTRODUCTION

Northern Hemisphere climate fluctuated on millennial to centennial time scales during the last deglaciation (ca. 19–6.5 ka) (see review of Alley and Clark, 1999). These climate oscillations are concurrent with reductions in Atlantic meridional overturning circulation (AMOC) strength, suggesting a causal link where reduced AMOC forced cooler and/or drier climate conditions around the North Atlantic region (e.g., Alley and Clark, 1999; Clark et al., 2001; McManus et al., 2004). While there is general consensus that reductions in AMOC strength were driven by increased freshwater discharge to the North Atlantic, the location, magnitude, and mechanisms of discharge remain unclear (Björck et al., 1996; Clark et al., 2001; Flower et al., 2004; McManus et al., 2004; Donnelly et al., 2005). Increased iceberg discharge associated with Heinrich Events occurred during the Oldest Dryas (ca. 18.0–14.7 ka) and Younger Dryas (ca. 12.9–11.5 ka) cold events (McManus et al., 2004), but increases in iceberg discharge lagged the onset of these AMOC reductions and terminated prior to AMOC resumptions (Clark et al., 2001; Carlson et al., 2008). Similarly, centennial-scale AMOC reductions may have punctuated the Bølling-Allerød warm periods (ca. 14.6–12.9 ka), possibly reflected in increased atmospheric $\Delta^{14}C$ values, which are not associated with increased iceberg discharge (Björck et al., 1996; Hughen et al., 2000; Clark et al., 2001; Donnelly et al., 2005).

A related mechanism that may reduce AMOC strength involves the routing of North American freshwater runoff from outlets farther from regions of deepwater formation to outlets closer to regions of deepwater formation (Clark et al., 2001). During the last deglaciation, retreat and readvance of the Laurentide Ice Sheet rerouted North American runoff multiple times through three main outlets: south through the Mississippi River, east through the Hudson and St. Lawrence Rivers, and north through the Mackenzie River (Fig. 1) (Licciardi et al., 1999). Throughout the Bølling-Allerød, the southern Laurentide Ice Sheet was situated roughly at the latitudes of

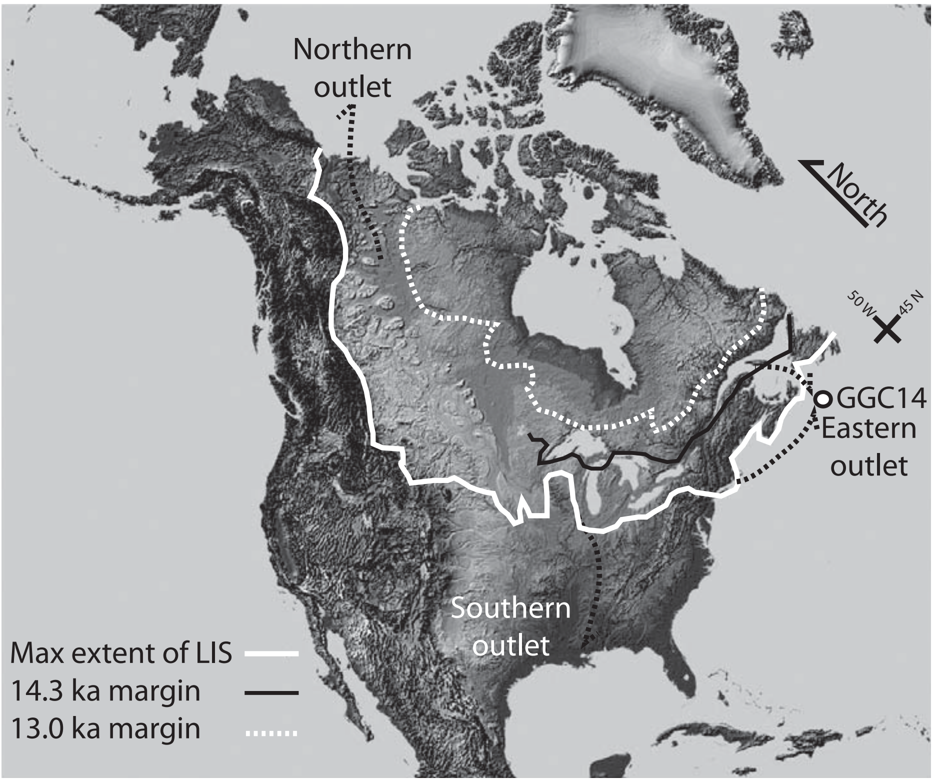

Figure 1. Map of Laurentide Ice Sheet (LIS) margins (Licciardi et al., 1999) and GGC14 core location. Solid white line shows glacial maximum extent, black line shows LIS extent ca. 14.3 ka, and dashed white line shows ca.13.0 ka extent. Dashed black lines with arrows denote locations of freshwater input to core GGC14 through Hudson and St. Lawrence Rivers. Southern outlet through Mississippi River and northern outlet through Mackenzie River are also shown.

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the eastern Great Lakes, and fluctuations of its southern margin may have periodically routed freshwater to the eastern outlets (Fig. 1) (Licciardi et al., 1999), possibly explaining the centennial-scale reductions in AMOC strength (Clark et al., 2001). Here we use geochemical marine records adjacent to the Hudson and St. Lawrence Rivers to examine whether freshwater discharge to the North Atlantic increased during these Bølling-Allerød routing events.

METHODS

We reconstruct calcification temperature (CT) and the salinity-dependent $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) from R/V *Oceanus* (OCE) core OCE326 GGC14 on the Laurentian Fan, ideally located to record eastward routing of freshwater through the St. Lawrence River and the Hudson River with subsequent advection to the core site in the Gulf Stream (Keigwin and Jones, 1995; Keigwin et al., 2005) (Fig. 1). Samples were collected at ~2 cm resolution, and ~25 *Neogloboquadrina pachyderma* sinistral (s) tests were picked for trace element analysis. This species lives at the thermocline (e.g., deVernal et al., 1996), or ~100 m water depth for the Laurentian Fan (Dickie and Trites, 1983). Mg/Ca ratios were measured by VG PQ ExCell Quadrupole inductively coupled plasma–mass spectrometry using the continuous time-resolved flow-through method developed by Haley and Klinkhammer (2002), and converted to CT (Figs. 2C and 2E) (Mashiotta et al., 1999). After correcting for ice volume effects on the $\delta^{18}O$ composition of the global ocean (Clark and Mix, 2002), $\delta^{18}O_{sw}$ is calculated with Mg/Ca-CT and the existing GGC14 *N. pachyderma* (s) $\delta^{18}O$ of calcite record (Figs. 2D and 2F) (Keigwin et al., 2005). The chronology of core GGC14 is based on 7 reservoir-corrected and calibrated radiocarbon dates (Keigwin et al., 2005) and a well-established $\delta^{18}O$ stratigraphy for the Laurentian Fan (30 radiocarbon dates) (Keigwin and Jones, 1995). We estimate changes in the freshwater discharge through the Hudson and St. Lawrence Rivers by applying the $\delta^{18}O_{sw}$ record to a freshwater-ocean mixing model (Carlson et al., 2007). See the GSA Data Repository[1] for in-depth discussion of methods, data, calibration error, core chronology, and the mixing model.

RESULTS

The Mg/Ca-CT thermocline record suggests an overall warming of ~8 °C from the early deglacial period (ca. 17.4 ka) to the early Holocene (ca. 10 ka) (Fig. 2C). Between ca. 17.4 and 14.6 ka, CT warmed ~5 °C, punctuated by 2 CT oscillations of 1–2 °C centered ca. 17.0 and 16.0 ka. St. Lawrence CT abruptly warmed ~2 °C ca. 14.6 ka, with subsequent cooling of ~2.5 °C from ca. 14.1 to 13.1 ka.

The $\delta^{18}O_{sw}$ thermocline record shows 0.5‰–0.6‰ lighter values ca. 17.4–14.7 ka relative to the early Holocene (11.3–10 ka), with a large $\delta^{18}O_{sw}$ decrease of 1.2‰ ca. 16.3–15.9 ka and a second oscillation of 0.5‰ ca. 15.0–14.8 ka (Fig. 2D). Between ca. 14.6 and 13.0 ka, $\delta^{18}O_{sw}$ oscillated on centennial time scales. Maxima are centered ca. 14.5, 14.0, and 13.7 ka, but with an overall decrease of ~0.9‰ in maximum values from ca. 14.5 to 13.2 ka. These maxima are terminated with decreases of 0.9‰, 0.5‰, and 0.4‰ ca. 14.1, 13.8, and 13.3 ka, respectively.

For the portion of our $\delta^{18}O_{sw}$ record spanning the Bølling-Allerød, we model with our freshwater-ocean mixing model (see the Data Repository) the freshwater discharge required to explain the decreases in $\delta^{18}O_{sw}$ using eastern Great Lakes freshwater runoff end-member values (Lewis and Anderson, 1992). The 0.9‰ decrease ca. 14.1 ka is explained by a freshwater discharge increase of 0.054 ± 0.006 Sverdrups (Sv, 10^6 m^{-3} s^{-1}). The ca. 13.8 ka decrease of 0.5‰ requires a 0.031 ± 0.004 Sv discharge increase and the ca. 13.3 ka decrease of 0.4‰ requires a 0.027 ± 0.003 Sv discharge increase. These increases are separated by decreases in modeled discharge of 0.028 ± 0.005 Sv ca. 14.0 ka, and 0.021 ± 0.003 Sv ca. 13.7 ka. We note that these modeled discharges may be slight underestimates as *N. pachyderma* (s) lives at ~100 m water depth, and thus may not record the full magnitude of freshwater discharge.

We have focused on the time interval prior to the Younger Dryas, in particular on the Bølling-Allerød (note that a manuscript is in preparation on the Younger Dryas section of GGC14; L. Keigwin, 2009, personal commun.). We analyze only five samples for Mg/Ca from the Younger Dryas interval; all show a gradual increase in Mg/Ca during the Younger Dryas (Fig. 2E), despite well-documented cooling of this region (e.g., Keigwin and Jones, 1995; deVernal et al., 1996). This is in agreement with another Younger Dryas trace element study in the St. Lawrence estuary (Carlson et al., 2007) that demonstrated that the Mg/Ca-CT relationship was compromised by the discharge of western Canadian Plains Mg-rich waters routed from the Mississippi River to the St. Lawrence River at the start of the Younger Dryas. We thus present the Mg/Ca data in Figure 2E but do not calculate a corresponding CT or $\delta^{18}O_{sw}$ for these samples. Note that this Mg-rich western Canadian Plains freshwater would not affect our samples from the pre-Younger Dryas period as this water was routed south to the Gulf of Mexico prior to ca. 12.9 ka (Licciardi et al., 1999; Clark et al., 2001; Flower et al., 2004; Carlson et al., 2007).

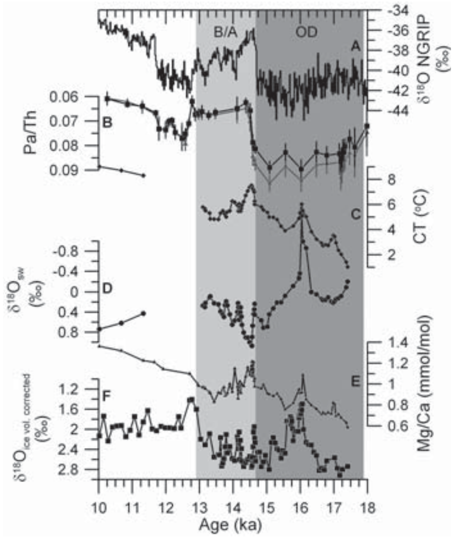

Figure 2. Deglacial records from GGC14, North Atlantic temperature, and Atlantic Meridional Overturning Circulation (AMOC) strength. A: North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ record (black step plot) (North Greenland Ice Core Project members, 2004). B: Pa/Th record of AMOC strength (gray 238 method, black 232 method) (McManus et al., 2004). C: GGC14 calcification temperature (CT) with 3-point smoothing (black diamonds). D: GGC14 $\delta^{18}O_{sw}$ (sw, seawater) with 3-point smoothing (black circles). E: GGC14 Mg/Ca (black triangles). F: $\delta^{18}O$ of calcite (Keigwin et al., 2005) corrected for ice volume (Clark and Mix, 2002) (black squares). Dark gray bar denotes timing of Oldest Dryas cold event (OD). Light gray bar shows Bølling-Allerød warm period (B/A).

DISCUSSION AND CONCLUSIONS

Our Mg/Ca-CT record shows gradual warming ca. 17.4–14.7 ka despite a reduction in AMOC strength (McManus et al., 2004), and relative cooling over Greenland (e.g., North Greenland Ice Core Project members, 2004) (Fig. 2) and in the eastern North Atlantic (e.g., Bard et al., 2000). However, a reduction in the abundance of polar foraminifera on the Laurentian Fan (Keigwin and Jones, 1995) supports the CT warming trend. This local warming during reduced AMOC of the Oldest Dryas may reflect a reduction in regional albedo from retreat of the Laurentide Ice Sheet (Ridge, 2004; Shaw et al., 2006). The abrupt ~2 °C warming ca. 14.6 ka is coincident with the onset of the Bølling while the subsequent cooler period ca. 14.1–13.1 ka is concurrent with the Allerød (Figs. 3A and 3E). The similarity in St. Lawrence CT and Summit, Greenland $\delta^{18}O$ during this interval suggests a tighter climate coupling between the two regions than during the Oldest Dryas, which may be a consequence of the Laurentide Ice Sheet being

[1]GSA Data Repository item 2010034, in-depth methods, model description, and data table, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

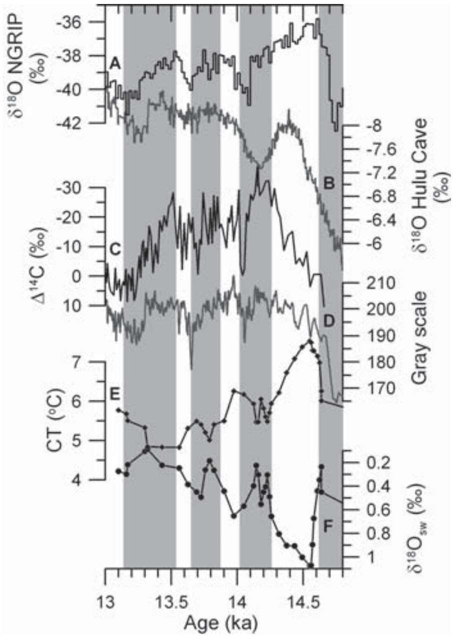

Figure 3. Atlantic Meridional Overturning Circulation (AMOC) strength and paleoclimate during Bølling-Allerød. A: North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ record (black step plot) (North Greenland Ice Core Project members, 2004). B: Hulu Cave $\delta^{18}O$ record of Southeast Asian Monsoon strength (gray step plot) (Wang et al., 2001). C: Detrended $\Delta^{14}C$, proxy of AMOC (black line) (Hughen et al., 2000). D: Cariaco Basin gray-scale record of trade wind strength (gray line) (Hughen et al., 1996). E: GGC14 Mg/Ca calcification temperature (CT; black diamonds). F: GGC14 $\delta^{18}O_{sw}$ (sw, seawater; black circles). Gray bars denote periods of increased runoff through eastern outlets and associated AMOC and climate changes.

farther from the St. Lawrence region (Ridge, 2004; Shaw et al., 2006), and thus a reduction in its effects on local climate.

The $\delta^{18}O_{sw}$ thermocline record has lower values ca. 17.4–14.7 ka relative to the early Holocene (Fig. 2D). The $\delta^{18}O_{sw}$ minimum ca. 16 ka is concurrent with a peak in ice-rafted debris (IRD) on the Laurentian Fan (Keigwin and Jones, 1995) and the collapse of ice over the St. Lawrence Estuary (Shaw et al., 2006). The timing of this IRD and $\delta^{18}O_{sw}$ pulse is near the end of Heinrich Event 1, suggesting that the southeastern Laurentide Ice Sheet contributed icebergs to this event (Keigwin and Jones, 1995; Keigwin et al., 2005). We attribute the overall decreased $\delta^{18}O_{sw}$ ca. 17.4–14.7 ka relative to the Holocene to increased freshwater discharge from Laurentide Ice Sheet retreat in New England and Maritime Canada (Ridge, 2004), and the eastward routing of Great Lakes Ontario, Erie, Huron, and Michigan through the Hudson River during the Mackinaw Interstade ca. 16–14.7 ka (Hansel and Mickelson, 1988; Licciardi et al., 1999).

The ~0.8‰ $\delta^{18}O_{sw}$ increase ca. 14.6 ka (Fig. 3F) indicates a reduction in freshwater runoff likely from the Port Huron readvance of the southern Laurentide Ice Sheet that routed eastern Great Lakes freshwater back into the Mississippi River drainage basin (Hansel and Mickelson, 1988; Licciardi et al., 1999); this is reflected in the Gulf of Mexico as an ~0.7‰ decrease in $\delta^{18}O_{sw}$ (Flower et al., 2004). A short-lived retreat during this readvance could explain the ~0.5‰ decrease ca. 14.8 ka. The subsequent Laurentian Fan $\delta^{18}O_{sw}$ minima ca. 14.1, 13.8, and 13.4–13.1 ka suggest periodic increases in freshwater discharge through the eastern outlets (Fig. 3F). The decrease in $\delta^{18}O_{sw}$ ca. 14.1 ka is concurrent with the retreat of the southern Laurentide Ice Sheet and eastward drainage of Great Lakes Ontario, Huron, and Erie through the Hudson River (Licciardi et al., 1999); the increase ca. 13.9 ka is in agreement with a short-lived southern Laurentide Ice Sheet margin readvance (Hansel and Mickelson, 1988). Similarly, the ca. 13.8 ka $\delta^{18}O_{sw}$ decrease is likely in response to further Laurentide Ice Sheet retreat that added Lake Michigan to the Hudson River drainage basin during the Two Creeks interstade, whereas the subsequent $\delta^{18}O_{sw}$ increase is from the Greatlakean readvance of the southern Laurentide Ice Sheet and southward rerouting of the Lake Michigan Basin (Hansel and Mickelson, 1988; Licciardi et al., 1999). The decrease in $\delta^{18}O_{sw}$ to a plateau ca. 13.4–13.1 ka records the opening of the St. Lawrence Valley and routing of eastern Great Lakes freshwater through the St. Lawrence River (Licciardi et al., 1999; Donnelly et al., 2005). We thus conclude that our new $\delta^{18}O_{sw}$ record agrees well with the southern Laurentide Ice Sheet margin chronology (Hansel and Mickelson, 1988; Licciardi et al., 1999).

The modeled increases in freshwater discharge of 0.03–0.05 Sv during the Bølling-Allerød are similar to, though slightly higher than, previous discharge estimates of 0.01–0.042 Sv based on ice sheet–atmosphere general circulation model (GCM) simulations (Licciardi et al., 1999). Our freshwater discharge increases are smaller than what has been traditionally used in fully coupled atmosphere-ocean GCM "hosing" experiments, where a 0.1 Sv freshwater discharge to the North Atlantic causes an ~30% reduction in AMOC strength (e.g., Stouffer et al., 2006). However, a fully coupled GCM with glacial boundary conditions simulated an ~20% reduction in AMOC strength in response to a freshwater discharge increase of 0.04 Sv to the North Atlantic (Liu et al., 2009); this is also observed in simpler climate models with local freshwater discharge (i.e., the St. Lawrence River) (Meissner and Clark, 2006), suggesting that our $\delta^{18}O_{sw}$-modeled discharge increases may have forced small (<25%) reductions in AMOC strength during the Bølling-Allerød. An additional source of freshwater ca. 13.4 ka may have come from the abrupt drainage of ice-dammed lakes along the southeastern Laurentide Ice Sheet margin just prior to the deglaciation of the St. Lawrence Valley, with a discharge of as high as 0.22 Sv for <0.5 yr (Donnelly et al., 2005).

Comparing our $\delta^{18}O_{sw}$ runoff record with proxies of AMOC indicates that periods of increased freshwater discharge through the eastern outlets were related to periods of reduced AMOC strength (Figs. 2B and 3C). The lower $\delta^{18}O_{sw}$ ca. 17.4–14.7 ka with a minimum ca. 16 ka (Fig. 2D) spans the decrease in AMOC strength during the Oldest Dryas (Fig. 2B) (McManus et al., 2004). Although we are unable to determine the discharge magnitude during this period because of a lack of a freshwater $\delta^{18}O$ end-member value (Lewis and Anderson, 1992), we suggest that the increased discharge may have maintained AMOC in a weakened though gradually increasing state following the end of Heinrich Event 1 ca. 16 ka (Carlson et al., 2008), in agreement with previous conclusions from the terrestrial Laurentide Ice Sheet chronology (Clark et al., 2001). The $\delta^{18}O_{sw}$ abruptly increased ca. 14.6 ka, coincident with a large increase in AMOC strength (McManus et al., 2004), suggesting a tight coupling between eastward freshwater routing and AMOC strength (Figs. 2 and 3). While the Pa/Th record of AMOC strength (McManus et al., 2004) shows little variability during the Bølling-Allerød, possibly due to its low resolution, high-resolution atmospheric $\Delta^{14}C$ records indicate $\Delta^{14}C$ increases of 20–25 ppm ca. 14.1, 13.7, and 13.3 ka (Fig. 3C), potentially implying reduced AMOC (Björck et al., 1996; Hughen et al., 2000; Clark et al., 2001). These increases in $\Delta^{14}C$ are similar in timing with the $\delta^{18}O_{sw}$ decreases in our record (Fig. 3). Although there appears to be a slight lead in $\delta^{18}O_{sw}$ decreases over $\Delta^{14}C$ increases, the uncertainty in the GGC14 chronology (i.e., ±50–100 yr; Keigwin et al., 2005) does not allow the establishment of such a relationship. Therefore, our $\delta^{18}O_{sw}$ record and its modeled discharges suggest that routing of freshwater through the eastern North American outlets probably caused these centennial-scale reductions in AMOC strength during the Bølling-Allerød (Clark et al., 2001).

Northern Hemisphere high-resolution paleoclimate records indicate centennial-scale climate changes coincident (within the uncertainties of radiocarbon dating) with the eastward routing of North American freshwater and attendant decreases in AMOC during the Bølling-Allerød. Summit Greenland ice cores show cooling ca. 14.1 ka during the Older Dryas cold period, ca. 13.8 ka, and ca. 13.2 ka, during the Intra-Allerød cold period (Fig. 3A), suggesting reductions in northward heat transport from reduced AMOC strength (Björck et al., 1996; Clark et al., 2001; Donnelly et al., 2005). These events are also recorded on the Laurentian Fan as CT cooling of 1–2 °C, synchronous with the decreases in $\delta^{18}O_{sw}$ and supporting our correlation with the Greenland ice core records (Fig. 3E). Southeast Asian Monsoon proxies indicate reductions in monsoon intensity during most of these intervals of eastward freshwater routing to the North Atlantic (Fig. 3B) (Wang et al., 2001). Likewise, concurrent increases in trade wind strength and upwelling in the Caraico Basin signify a southward shift in the Intertropical Convergence Zone (ITCZ) (Fig. 3D) (Hughen et al., 1996; Clark et al., 2001). These teleconnections between eastward freshwater routing, AMOC strength, northward heat transport, monsoon intensity, and ITCZ position have been previously established on millennial time scales (e.g., Hughen et al., 1996; Wang et al., 2001; Clark et al., 2001; Carlson et al., 2007, 2008). Here we confirm that despite the smaller magnitude of freshwater discharge and the AMOC-climate response, these same processes and teleconnections were likely operating on centennial time scales (Björck et al., 1996; Hughen et al., 1996; Clark et al., 2001). Moreover, the hemispheric impact of these reductions in AMOC strength demonstrates the sensitivity of the climate system to relatively small changes in the freshwater budget of the North Atlantic.

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