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Linking the 8.2 ka event and its freshwater forcing in the Labrador Sea

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[1] The 8.2 ka event was the last deglacial abrupt climate event. A reduction in the Atlantic meridional overturning circulation (AMOC) attributed to the drainage of glacial Lake Agassiz may have caused the event, but the freshwater signature of Lake Agassiz discharge has yet to be identified in δ^{18}O of foraminiferal calcite records from the Labrador Sea, calling into question the connection between freshwater discharge to the North Atlantic and AMOC strength. Using Mg/Ca-paleothermometry, we demonstrate that ~3°C of near-surface ocean cooling masked an ~1.0‰ decrease in western Labrador Sea δ^{18}O of seawater concurrent with Lake Agassiz drainage. Comparison with North Atlantic δ^{18}O of seawater records shows that the freshwater discharge was transported to regions of deep-water formation where it could perturb AMOC and force the 8.2 ka event. **Citation:** Hoffman, J. S., A. E. Carlson, K. Winsor, G. P. Klinkhammer, A. N. LeGrande, J. T. Andrews, and J. C. Strasser (2012), Linking the 8.2 ka event and its freshwater forcing in the Labrador Sea, *Geophys. Res. Lett.*, *39*, L18703, doi:10.1029/2012GL053047.

1. Introduction

[2] The 8.2 ka event is recorded in numerous paleoclimate records throughout the Northern Hemisphere [*Alley et al.*, 1997; *Alley and Ágústdóttir*, 2005; *Rohling and Pälike*, 2005]. Proxies of Atlantic meridional overturning circulation (AMOC) (e.g., sortable silt, benthic δ^{13}C) indicate a reduction in AMOC during the 8.2 ka event, suggesting the involvement of AMOC variability in this abrupt climate event [*Ellison et al.*, 2006; *Kleiven et al.*, 2008; *Hoogakker et al.*, 2011]. Earlier abrupt climate events with a similar climatic footprint are linked to increased freshwater discharge to the North Atlantic and subsequent reductions in AMOC strength [*Clark et al.*, 2001], leading to the hypothesis that increased North Atlantic freshwater discharge likewise caused the 8.2 ka event [*Klitgaard-Kristensen et al.*, 1998; *Barber et al.*, 1999; *Clark et al.*, 2001; *Ellison et al.*, 2006; *LeGrande et al.*, 2006; *Came et al.*, 2007].

[3] During the last deglaciation, large proglacial lakes formed between the retreating Laurentide Ice Sheet margin and the isostatically depressed landscape [*Teller et al.*, 2002]. Lake volume reached a maximum (40,000–151,000 km^3) when glacial Lake Ojibway combined with Lake Agassiz just prior to ~8.5 ka [*Teller et al.*, 2002; *Clarke et al.*, 2004]. Upon collapse of the Laurentide Ice Sheet over Hudson Bay shortly after ~8.5 ka [*Barber et al.*, 1999], Lake Agassiz drained through Hudson Bay into the Labrador Sea at an estimated discharge of ~5 Sverdrups (Sv, 10^6 m^3 s^{-1}) in one to several ~6-month -long flood(s) [*Andrews et al.*, 1995, 1999; *Kerwin*, 1996; *Clarke et al.*, 2004; *Ellison et al.*, 2006; *Hillaire-Marcel et al.*, 2007; *Lajeunesse and St-Onge*, 2008; *Clarke et al.*, 2009; *Roy et al.*, 2011; *Lewis et al.*, 2012]. In addition to the freshwater forcing from the flood(s), collapse of the Laurentide Ice Sheet also routed Lake Agassiz runoff through Hudson Strait [*Clark et al.*, 2001; *Hillaire-Marcel et al.*, 2007; *Clarke et al.*, 2009] for several hundred years at a discharge of 0.13 ± 0.03 Sv [*Carlson et al.*, 2009]. If this freshwater reached regions of deep-water formation in the North Atlantic, it could have capped surface water and disrupted the AMOC [*Ellison et al.*, 2006; *Kleiven et al.*, 2008; *Hoogakker et al.*, 2011]. The relatively close timing of the 8.2 ka event [*Alley et al.*, 1997; *Alley and Ágústdóttir*, 2005; *Rohling and Pälike*, 2005] and the drainage of Lake Agassiz suggests a causal relationship where lake drainage and attendant runoff routing could have forced this abrupt climate event [*Klitgaard-Kristensen et al.*, 1998; *Barber et al.*, 1999; *Clark et al.*, 2001; *Teller et al.*, 2002; *LeGrande et al.*, 2006; *Hillaire-Marcel et al.*, 2007; *Clarke et al.*, 2009; *Carlson et al.*, 2009; *Lewis et al.*, 2012].

[4] Sediment and faunal records from James and Hudson Bays, Hudson Strait, and the Labrador Sea support the drainage of Lake Agassiz around 8.2 ka [*Andrews et al.*, 1995, 1999; *Kerwin*, 1996; *Barber et al.*, 1999; *Hillaire-Marcel et al.*, 2007; *Lajeunesse and St-Onge*, 2008; *Roy et al.*, 2011; *Lewis et al.*, 2012], and Hudson Strait geochemical records document the routing of Lake Agassiz drainage basin runoff during the 8.2 event [*Carlson et al.*, 2009]. However, no direct evidence of a freshwater signal has been found in Labrador Sea δ^{18}O of foraminiferal calcite ($\delta^{18}O_c$) coeval with the drainage of Lake Agassiz [*Keigwin et al.*, 2005; *Hillaire-Marcel et al.*, 2007, 2008]. One explanation for the lack of a $\delta^{18}O_c$ signal is that the lake drainage was too short lived to be recorded by planktonic foraminifera [*Andrews et al.*, 1999; *Hillaire-Marcel et al.*, 2007], although

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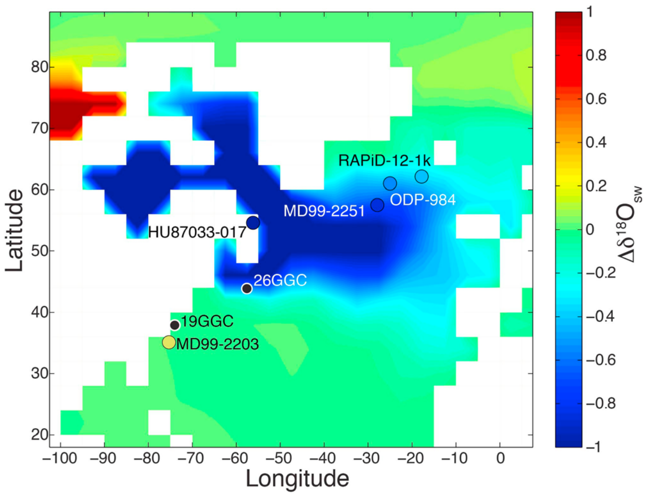

Figure 1. Locations of cores HU87033-017 (54.6°N, 56.2°W; this study), MD99-2203 (35.0°N, 75.2°W) [*Cléroux et al.*, 2012], MD99-2251 (57.4°N, 27.9°W) [*Ellison et al.*, 2006], ODP Site 984 (61.0°N, 25.0°W) [*Came et al.*, 2007], and RAPiD-12-1K (62.1°N, 17.8°W) [*Thornalley et al.*, 2009] indicated by circles with color showing observed $\delta^{18}O_{sw}$ anomaly during the 8.2 ka event. Black circles indicate locations of decreases in $\delta^{18}O$ of calcite [*Keigwin et al.*, 2005]; $\delta^{18}O_{sw}$ changes for these records are not displayed because temperature effects have not been assessed. Also shown is the GISS ModelE-R simulated change in surface ocean $\delta^{18}O_{sw}$ one decade after the addition of 5 Sv of freshwater in 0.5 years [*LeGrande and Schmidt*, 2008] ($\delta^{18}O$ of −25‰) [*Hillaire-Marcel et al.*, 2008] into Hudson Strait with an already weakened convection in the Labrador Sea (run WK 5 Sv × 0.5 year) [*LeGrande and Schmidt*, 2008]. Note that the foraminifera records reflect $\delta^{18}O_{sw}$ changes at the preferred depth of foraminifera, which may be deeper than the modeled surface ocean $\delta^{18}O_{sw}$ changes.

a longer $\delta^{18}O_c$ decrease should be evident from the breakup of the Laurentide Ice Sheet over Hudson Bay [*Andrews et al.*, 1995, 1999] and the addition of the Lake Agassiz drainage basin to Hudson Bay [*Clark et al.*, 2001; *Hillaire-Marcel et al.*, 2007; *Carlson et al.*, 2009]. Another explanation is that the discharged freshwater may have had little impact on Labrador Sea $\delta^{18}O_c$ because Lakes Agassiz and Ojibway $\delta^{18}O$ of approximately −25‰ was only marginally more negative than present-day runoff to James and Hudson Bays of −20‰ [*Hillaire-Marcel et al.*, 2008]. However, even without a change in runoff $\delta^{18}O$, an increase in freshwater discharge as expected during Lake Agassiz drainage would still cause a decrease in Labrador Sea $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) due to the increased volume of ^{18}O-depleted freshwater [*Barber et al.*, 1999; *LeGrande et al.*, 2006]. Attributing the cause of the reduction in AMOC during the 8.2 ka event to the drainage of Lake Agassiz has also proven difficult, because Lake Agassiz discharge may have been mostly trapped against the Labrador shelf in a buoyant surface flow of the Labrador Current and not transported to regions of deep convection in the open ocean [*Wunsch*, 2010; *Condron and Winsor*, 2011]. These outstanding issues ultimately imply that freshwater discharge may not have caused the 8.2 ka event, raising the possibility that alternative mechanisms, like reduced solar activity, forced this and other abrupt climate events [*Alley and Ágústdóttir*, 2005; *Rohling and Pälike*, 2005]. Because $\delta^{18}O_c$ is sensitive to changes in surface temperatures and local $\delta^{18}O_{sw}$ [e.g., *LeGrande et al.*, 2006], we hypothesize that the magnitude of near-surface cooling during the 8.2 ka event masked a $\delta^{18}O_{sw}$ decrease in Labrador Sea $\delta^{18}O_c$ from the drainage of Lake Agassiz.

2. Methods

[5] We test our hypothesis with core HU87033-017 from the Cartwright Saddle (54.62°N, 56.18°W, 514 m water depth) (Figure 1 and auxiliary material, Text S1, section S1), which is located in the pathway Lake Agassiz discharge would have taken upon exiting Hudson Strait [*Condron and Winsor*, 2011].[1] We investigate early Holocene sediment discharge from the Laurentide Ice Sheet with changes in weight percent coarse fraction (>63 μm). We document western Labrador Sea calcification temperatures (CT) of *Neogloboquadrina pachyderma* (sinistral) with flow-through Mg/Ca-paleothermometry (Text S1, section S4) [*Klinkhammer et al.*, 2004]. *N. pachyderma* (s) is a pycnocline dwelling subpolar to polar planktonic foraminifer (Figure S1 and Text S1, sections S2 and S7). Combining our Mg/Ca CT record with the existing $\delta^{18}O_c$ record of *Andrews et al.* [1999] from HU87033-017, we calculate $\delta^{18}O_{sw}$ (Text S1, sections S4–S8). Due to the low abundance of planktonic foraminifera tests, the core chronology is based on eight benthic, reservoir-corrected (450 years), calibrated ^{14}C dates of *Andrews et al.* [1999] (Table S1 and Text S1, section S3).

3. Results

[6] Our new grain size record for this core identifies an abrupt ~20% increase in weight percent coarse fraction (>63 μm) dated at ~8.5–8.3 ka (Figure 2b), similar to the ~10% increase in the existing >125 μm record of *Andrews et al.* [1999]. This layer lies directly above the final deglacial increase in weight percent calcite and dolomite [*Andrews et al.*, 1999] (Figure 2b). The <63 μm fraction of these layers has a reddish hue, indicative of sediment deposited during the drainage of Lake Agassiz [*Andrews et al.*, 1995, 1999; *Kerwin*, 1996; *Barber et al.*, 1999]. Because Lake Agassiz resided over Paleozoic carbonates, its waters were depleted in ^{14}C, with a lower $^{14}C/^{12}C$ ratio equivalent to an age of ≥310 years [*Barber et al.*, 1999]. Indeed, if we apply an additional reservoir age (ΔR) of 310 years to the two radiocarbon dates within the carbonate and sand layers to reflect the influence of dissolved Paleozoic carbonate on Lake Agassiz runoff $^{14}C/^{12}C$ and potentially enhanced sea-ice cover in the early Holocene [*Jennings et al.*, 1998; *Andrews et al.*, 1999; *Barber et al.*, 1999; *Lewis et al.*, 2012], the age of this layer decreases to ~8.3–8.0 ka, coincident with the 8.2 ka event (Figure 2a and Table S1). We use this revised chronology for discussion of the CT and $\delta^{18}O_{sw}$ records, but note that regardless of the precise timing, the sedimentology and color of the sediment layers tie them to the drainage of Lake Agassiz [*Andrews et al.*, 1995, 1999; *Kerwin*, 1996; *Barber et al.*, 1999; *Hillaire-Marcel et al.*, 2007].

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053047.

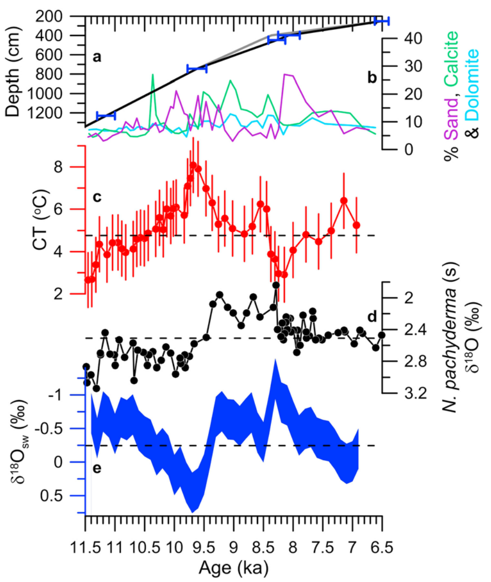

Figure 2. HU87033-017 records. (a) Age-depth relationship with blue error bars indicating ^{14}C dates [*Andrews et al.*, 1999]. Black is the age model discussed in the text with an additional 310 yr ΔR [*Barber et al.*, 1999; *Andrews et al.*, 1999], gray shows the age model without the additional ΔR. (b) Weight percent sand >63 μm (purple), calcite (light green) and dolomite (light blue) [*Andrews et al.*, 1999]. (c) Mg/Ca calcification temperature (CT) with $\pm$1.3°C uncertainty indicated. (d) *N. pachyderma* (s) $\delta^{18}O_c$ [*Andrews et al.*, 1999]. (e) $\delta^{18}O_{sw}$ with propagated CT and $\delta^{18}O_c$ uncertainty ($\pm$0.3‰). Horizontal dashed lines denote CT, $\delta^{18}O_c$, and $\delta^{18}O_{sw}$ data from 49 cm core depth.

[7] The *N. pachyderma* (s) CT record shows ~2°C of warming ~11.5–11.2 ka, with a more gradual trend to a CT maximum of ~8°C at ~9.7 ka (Figure 2c). CT subsequently cooled to 5–6°C between ~9.5 and 8.3 ka, reaching a minimum of ~3°C at ~8.3 ka. At ~8.0 ka, CT warmed to ~4°C and reached ~5°C by ~7.5 ka, which is equivalent to late Holocene CT (Figure S1 and Text S1, section S7). Our $\delta^{18}O_{sw}$ record shows several deviations from the *N. pachyderma* (s) $\delta^{18}O_c$ record of *Andrews et al.* [1999] (Figures 2d and 2e). Between ~11.2 and 9.7 ka, $\delta^{18}O_c$ increased by ~0.4‰, whereas $\delta^{18}O_{sw}$ increased by ~1.2‰; thereafter, both records decreased by ~1.0‰. At the same core depth as the ~3°C of CT cooling but just preceding the increase in weight percent sand, $\delta^{18}O_{sw}$ further decreased by ~1.0‰. $\delta^{18}O_{sw}$ then increased by ~0.9‰ after ~8.0 ka, and by another ~0.4‰ by ~7.0 ka.

4. Discussion and Conclusions

[8] The gradual increase in $\delta^{18}O_{sw}$ ~11.5–9.7 ka may document the stabilization of the Laurentide Ice Sheet margin as it retreated onto the Labrador coast [*Andrews et al.*, 1995, 1999]. The subsequent decrease after ~9.7 ka (Figure 2b) likely reflects increased iceberg calving and meltwater plume deposition of sediment from renewed Laurentide retreat and the beginning of ice break-up in Hudson Strait after the Noble Inlet readvance, which is supported by the increase in weight percent sand (Figure 2b) from sediment in meltwater plumes and icebergs [*Andrews et al.*, 1995, 1999; *Jennings et al.*, 1998].

[9] The ~1.0‰ further decrease in $\delta^{18}O_{sw}$ ~8.3–8.0 ka identifies increased freshwater discharge into the Labrador Sea coincident with the drainage of Lake Agassiz. This depletion event was obscured in the $\delta^{18}O_c$ record by the contemporaneous CT cooling of ~3°C in the Labrador Sea that reflects the impact of cold Lake Agassiz runoff and regional cooling during the 8.2 ka event. The masking of this $\delta^{18}O_c$ depletion by CT cooling is supported by climate model simulations of the break down in the relationship between temperature and $\delta^{18}O$ of foraminiferal calcite during the 8.2 ka event [*LeGrande et al.*, 2006], which is also observed at different subsurface depths in the North Atlantic with the application of Mg/Ca paleothermometry [*Came et al.*, 2007; *Thornalley et al.*, 2009]. Earlier studies of the Labrador Sea did not account for the effect of ocean cooling on $\delta^{18}O_c$ during the 8.2 ka event, explaining why a $\delta^{18}O_c$ decrease from the drainage of Lake Agassiz was previously suggested to be lacking [*Keigwin et al.*, 2005; *Hillaire-Marcel et al.*, 2007, 2008].

[10] The initiation of the ~8.3 ka $\delta^{18}O_{sw}$ decrease coincident with increased weight percent calcite and dolomite [*Andrews et al.*, 1999] detects the arrival of Lake Agassiz freshwater [*Andrews et al.*, 1995, 1999; *Kerwin*, 1996; *Barber et al.*, 1999; *Hillaire-Marcel et al.*, 2007]. The ensuing increase in weight percent sand probably records iceberg rafting and meltwater plume deposition of sediment during the breakup of the Laurentide Ice Sheet over Hudson Bay (Figure 2) [*Andrews et al.*, 1995, 1999]. Although multiple Lake Agassiz drainage events may have occurred leading to the final opening of Hudson Bay, the temporal spacing of these has yet to be quantified and was likely in a short interval of time [*Clarke et al.*, 2004; *Ellison et al.*, 2006; *Hillaire-Marcel et al.*, 2007; *Lajeunesse and St-Onge*, 2008; *Roy et al.*, 2011]. The $\delta^{18}O_{sw}$ anomaly does not show multiple peaks that would be expected from two or more Lake Agassiz drainage events (Figure 3e), and thus may record the final drainage event or integrate several drainage events due to our sampling resolution relative to the hypothesized months-long duration of the drainage events. The $\delta^{18}O_{sw}$ anomaly also persisted longer than the carbonate anomaly, likely reflecting both the final break-up of the Laurentide Ice Sheet, suggested by the sand layer [*Andrews et al.*, 1995, 1999] (Figure 2), and sustained Lake Agassiz runoff routing to the Labrador Sea for several hundred years after lake drainage [*Clark et al.*, 2001; *Hillaire-Marcel et al.*, 2007; *Carlson et al.*, 2009].

[11] We compare our $\delta^{18}O_{sw}$ decrease with other records of freshwater discharge during the 8.2 ka event to trace the path of freshwater from Hudson Bay. After flowing through Hudson Strait, we document the drainage of Lake Agassiz in the western Labrador Sea with the ~1.0‰ $\delta^{18}O_{sw}$ decrease. In the northwest Atlantic at 43–37°N, $\delta^{18}O_c$ records show depletions of 0.4–0.6‰, reflecting warming and/or increased freshwater discharge [*Keigwin et al.*, 2005]. However, $\delta^{18}O_{sw}$ increases by ~0.2‰ at 35°N in the northwest Atlantic (Figure 1) [*Cléroux et al.*, 2012]. In contrast, $\delta^{18}O_{sw}$ decreases in the northeast Atlantic of ~0.8‰ at ~27°W to ~0.4‰ at ~18°W from foraminifera living at different subsurface water depths (Figures 1 and 3) [*Ellison et al.*, 2006; *Came et al.*, 2007; *Thornalley et al.*, 2009]. These records thus document the dispersal of Lake Agassiz freshwater

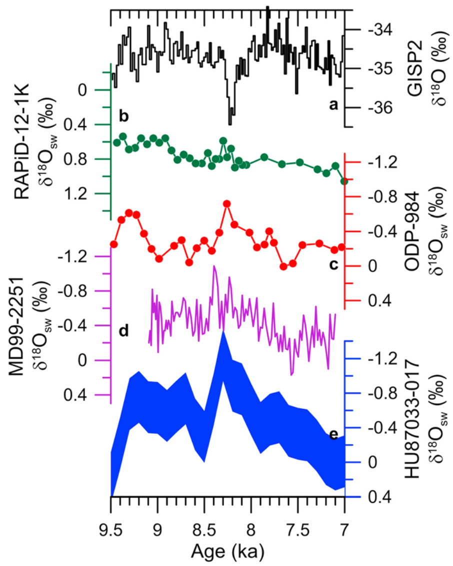

Figure 3. 8.2 ka event records. (a) GISP2 δ^{18}O [*Alley et al.*, 1997], and North Atlantic $\delta^{18}O_{sw}$ records for (b) RAPiD-12-1K on *Globorotalia inflata* [*Thornalley et al.*, 2009], (c) ODP Site 984 on *Neogloboquadrina pachyderma* (dextral) [*Came et al.*, 2007], (d) MD99-2251 on *Globigerina bulloides* using the preferred age model of the original authors [*Ellison et al.*, 2006], and (e) HU87033-017 on *N. pachyderma* (s).

across the North Atlantic, with freshwater transported southwards as far as ~37°N in the northwest Atlantic, and eastward into the northeast Atlantic. The decrease in $\delta^{18}O_{sw}$ anomalies to the south and east of the Labrador Sea likely shows the dilution of the freshwater signal along these transport paths (Figure 1).

[12] A 10-year simulation with the MITgcm high-resolution (0.167° × 0.167°) ocean-ice model suggested that a 1-year freshwater discharge through Hudson Strait would not reach deep-water formation sites and would rather be entrained into the subtropical gyre as far south as 25°N near the Florida Strait [*Condron and Winsor*, 2011], conflicting with available $\delta^{18}O_{sw}$ records (Figures 1 and 3) [*Ellison et al.*, 2006; *Came et al.*, 2007; *Thornalley et al.*, 2009; *Cléroux et al.*, 2012]. The 10-year duration of the MITgcm simulation may be of insufficient length to model the transport of Lake Agassiz discharge from Hudson Strait to the northeast Atlantic. The simulations also did not include the longer-duration freshwater discharge from Laurentide Ice Sheet retreat and continental rerouting [*Andrews et al.*, 1995, 1999; *Clark et al.*, 2001; *Hillaire-Marcel et al.*, 2007; *Carlson et al.*, 2009] that could have larger effects on AMOC strength [*Meissner and Clark*, 2006; *Clarke et al.*, 2009].

[13] Conversely, the UVic high-resolution (0.2° × 0.4°) ocean model that includes a simplified atmosphere found that freshwater on the Labrador shelf could affect the AMOC within years of its discharge [*Spence et al.*, 2008]. In addition, the UVic model simulated that the duration and maximum amplitude of the freshwater forcing and AMOC response are relatively insensitive to increasing resolution from low-resolution general circulation models (GCM) to high, eddy-resolving resolution [*Spence et al.*, 2008]. We also find agreement between changes in $\delta^{18}O_{sw}$ by the NASA Goddard Institute for Space Studies fully-coupled GCM ModelE-R that includes water isotopes throughout the hydrologic cycle [*LeGrande and Schmidt*, 2008] and the observed decrease in $\delta^{18}O_{sw}$ records during the 8.2 ka event (Figure 1), similar to other coupled climate model studies [*Meissner and Clark*, 2006; *Spence et al.*, 2008; *Clarke et al.*, 2009]. These model-$\delta^{18}O_{sw}$ comparisons suggest that although Lake Agassiz runoff may have been initially trapped in boundary currents along eastern North America [*Keigwin et al.*, 2005; *Wunsch*, 2010; *Condron and Winsor*, 2011], the freshwater eventually escaped from the continental shelf, was entrained in the Gulf Stream and North Atlantic Current, and reached regions of deep-water formation in the northeast Atlantic where it could affect the AMOC [*Ellison et al.*, 2006; *Kleiven et al.*, 2008; *Hoogakker et al.*, 2011].

[14] In conclusion, we document substantial near-surface cooling of the Labrador Sea during the 8.2 ka event. After accounting for this cooling, our $\delta^{18}O_{sw}$ record shows a significant decrease due to the drainage of Lake Agassiz; a signal that was previously masked in $\delta^{18}O_c$ records by the near-surface cooling. When combined with $\delta^{18}O_{sw}$ records from elsewhere in the North Atlantic, we can trace the pathway of Lake Agassiz discharge from Hudson Strait to regions of deep-water formation in the northeast Atlantic, supporting the hypothesis that the drainage of Lake Agassiz and attendant runoff routing into the Labrador Sea forced the 8.2 ka event [*Klitgaard-Kristensen et al.*, 1998; *Barber et al.*, 1999; *Clark et al.*, 2001; *Teller et al.*, 2002; *LeGrande et al.*, 2006; *Hillaire-Marcel et al.*, 2007; *Clarke et al.*, 2009; *Carlson et al.*, 2009].

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