GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L14704, doi:10.1029/2009GL038778, 2009

Routing of western Canadian Plains runoff during the 8.2 ka cold event

Anders E. Carlson,[1] Peter U. Clark,[2] Brian A. Haley,[3] and Gary P. Klinkhammer[4]

Received 19 April 2009; accepted 15 June 2009; published 18 July 2009.

[1] The collapse of the Laurentide Ice Sheet over Hudson Bay ∼8.47 ka allowed the rapid drainage of glacial Lake Agassiz into the Labrador Sea, an event identified as causing a reduction in Atlantic meridional overturning circulation (AMOC) and the 8.2 ka cold event. Atmosphere-ocean models simulations based on this forcing, however, fail to reproduce several characteristics of this event, particularly its duration. Here we use planktonic foraminifera U/Ca records to document the routing of western Canadian Plains runoff that accompanied ice-sheet collapse. Geochemical modeling of the ∼7 nmol/mol increase in U/Ca at the opening of Hudson Bay indicates an increase in freshwater discharge of 0.13 ± 0.03 Sverdrups (10^6 m^3 s^{-1}) from routing, a sufficient magnitude to cause an AMOC reduction. We suggest that this routing event suppressed AMOC strength for several centuries after the drainage of Lake Agassiz, explaining multi-centennial climate anomalies associated with the 8.2 ka cold event. **Citation:** Carlson, A. E., P. U. Clark, B. A. Haley, and G. P. Klinkhammer (2009), Routing of western Canadian Plains runoff during the 8.2 ka cold event, *Geophys. Res. Lett.*, *36*, L14704, doi:10.1029/2009GL038778.

1. Introduction

[2] The 8.2 ka cold event is the most prominent climate anomaly of the Holocene in Greenland ice core $\delta^{18}O$ records [*Alley et al.*, 1997], with the coldest portion of the ∼160 year-long event lasting ∼70 years [*Thomas et al.*, 2007]. This event is commonly attributed to the opening of Hudson Bay 8.47 ± 0.2 ka (or shortly thereafter, given the conservative estimate of the Hudson Bay reservoir age) from the collapse of the overlying Laurentide Ice Sheet and the attendant rapid drainage of glacial Lake Agassiz through Hudson Strait into the Labrador Sea [*Barber et al.*, 1999]. Glacio-hydrologic modeling suggests a flood discharge of ∼5 Sverdrups (Sv, 10^6 m^3 s^{-1}) over a period of ∼0.5 years [*Clarke et al.*, 2004], while sea surface salinity proxies from the northeastern Atlantic indicate abrupt freshening concurrent with this flood, suggesting that the freshwater was transported to regions of North Atlantic convection and deepwater formation [*Ellison et al.*, 2006; *Came et al.*, 2007].

[3] Although simulations with climate models indicate that this flood was large enough to have forced a decades-long reduction in Atlantic meridional overturning circulation (AMOC) strength with attendant cooling of the North Atlantic region [*LeGrande et al.*, 2006; *Meissner and Clark*, 2006; *LeGrande and Schmidt*, 2008], proxy records suggest greater complexity and duration to the event. AMOC proxy records, for example, show centennial-scale reduction in AMOC strength with a minimum at ∼8.3 ka [*Ellison et al.*, 2006; *Kleiven et al.*, 2008]. Similarly, climate anomalies correlated to the 8.2 ka cold event are several centuries in duration and have been attributed to a reduction in solar activity [e.g., *Alley and Ágústdóttir*, 2005; *Rohling and Pälike*, 2005]. Another possible explanation for a centuries-long climate response is the presence of an additional freshwater forcing. Indeed, associated with the collapse of ice over Hudson Bay was the rerouting of runoff from the western Canadian Plains to the Hudson Strait drainage basin, increasing the basin area by ∼3.4 × 10^6 km^2 (Figure 1) [*Licciardi et al.*, 1999; *Clark et al.*, 2001; *Clarke et al.*, 2009]. Here we use planktonic U/Ca records from Hudson Strait and a geochemical mixing model to investigate the magnitude of the freshwater forcing (precipitation less evaporation plus ice melt flowing over bedrock) from this routing of western Canadian Plains runoff associated with the 8.2 ka cold event.

2. U/Ca Records From Hudson Strait

[4] The dissolved geochemistry of river water reflects the underlying bedrock geochemistry, providing a tracer of water provenance [*Meybeck*, 1987]. Because western Canadian Plains freshwater has high concentrations of U relative to the global average, reflecting the U-rich underlying sedimentary bedrock (Saskatchewan Watershed Authority data) [*Palmer and Edmond*, 1993; *Carlson et al.*, 2007], the discharge of freshwater from this region through Hudson Strait should increase the U/Ca ratio in *Neogloboquadrina pachyderma* (s) tests [*Russell et al.*, 1994; *Carlson et al.*, 2007].

[5] To detect the input of freshwater derived from the western Canadian Plains, we measured U/Ca in tests of the polar planktonic foraminifera *N. pachyderma* (s). We sampled two cores collected from the eastern basin of Hudson Strait: HU93034-002 (60.95 °N, 65.70 °W, 822 m water depth) and HU93034-004 (61.22 °N, 66.43 °W, 526 m water depth) (Figure 1). These cores have several existing radiocarbon dates (Table S1 of the auxiliary material), and well-documented stratigraphies that allow the identification of the low magnetic susceptibility sediment layer and benthic faunal assemblages related to the opening of Hudson Bay [*Kerwin*, 1996; *Jennings et al.*, 1998; 2001; *Barber et al.*, 1999; *MacLean et al.*, 2001].[1] We note that *Barber et al.* [1999] used core 004 to date the opening of Hudson Bay,

[1]Deptartment of Geology and Geophysics, University of Wisconsin-Madison, Madison, Wisconsin, USA.
[2]Department of Geosciences, Oregon State University, Corvallis, Oregon, USA.
[3]Leibniz Institute of Marine Sciences, University of Kiel, Kiel, Germany.
[4]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

0094-8276/09/2009GL038778$05.00

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038778.

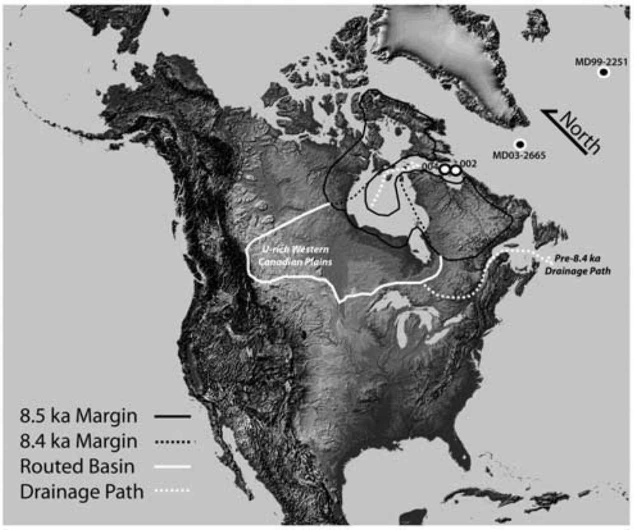

Figure 1. Map of early Holocene Laurentide Ice Sheet margins (black line ~8.5 ka margin, dashed black line changes by ~8.4 ka) [*Dyke*, 2004] and core locations. The Western Canadian Plains basin that was routed through Hudson Strait is outlined in white with basin routing prior to and after the opening of Hudson Bay shown by dashed white lines [*Licciardi et al.*, 1999]. White circles/black outlines indicate the location of cores HU93034-002 (002) and HU93034-004 (004). Black circles/white outlines denote location of cores MD03-2665 (57.44 °N, 48.60 °W, 3440 m water depth) [*Kleiven et al.*, 2008] and MD99-2251 (57.45 °N, 27.91 °W, 2620 m water depth) [*Ellison et al.*, 2006].

and its radiocarbon-dated stratigraphy is well correlated to core 002 [*Jennings et al.*, 1998, 2001; *MacLean et al.*, 2001] (Figure 2).

[6] Planktonic foraminifera abundances were low in all samples investigated, similar to previous studies [*Jennings et al.*, 2001], thus limiting the number of analyses to those presented here. In core 002, one sample was analyzed from before and three samples analyzed from after the opening of Hudson Bay. In core 004, two samples were analyzed from before and four samples from after the opening of Hudson Bay. Samples were physically cleaned and at least 35 tests were picked per sample. U/Ca was measured by inductively coupled mass spectrometry after isolating pure biogenic calcite from calcite overgrowths and clay contaminants using the flow-through methodology developed by *Haley and Klinkhammer* [2002].

[7] Our results identify a significant increase in U/Ca after the opening of Hudson Bay (Figure 2 and Table S2). The three samples from prior to the opening of Hudson Bay have average test U/Ca values of 2.0 ± 0.8 nmol/mol, whereas U/Ca increases to 9.0 ± 1.5 nmol/mol following the opening of Hudson Bay (average of 5 samples). Two samples from core 002 indicate a subsequent decrease in U/Ca to 2.7 ± 0.8 nmol/mol. These changes in U/Ca may reflect the reworking of the planktonic foraminifera in the sediment, but we consider this to be unlikely because the two cores are ~40 km apart (Figure 1) yet show essentially the same changes in U/Ca (Figure 2). Furthermore, planktonic foraminifera are low in abundance and the reworking of sediment from closer to the ice margin (e.g., from the Lake Agassiz flood) (Figure 1) would only introduce sediment with even fewer planktonic foraminifera. We thus conclude that the changes in U/Ca do not reflect reworking of sediment but rather reflect real changes in estuary water geochemistry.

[8] We note that environmental mechanisms other than changes in estuary geochemistry may have caused the observed changes in foraminifera U/Ca. For example, *Russell et al.* [2004] demonstrated that increased carbonate ion concentration reduced the U/Ca ratio in foraminifera tests. Because the opening of Hudson Bay added a drainage basin containing carbonate bedrock, the carbonate ion concentration in the estuary likely increased (Saskatchewan Watershed Authority Data), which would decrease the U/Ca signal, opposite to the observed signal. Changes in water temperature may also affect foraminifera U/Ca, with a positive relationship between temperature and U/Ca [*Yu et al.*, 2008]. However, water temperature changes in Hudson Strait were likely minimal during this period, because the only planktonic foraminifera present in all of the samples is *N. pachyderma* (s) indicating mixed layer temperatures of <5 °C [*Hilbrecht*, 1996]. Furthermore, the North Atlantic region cooled during this interval [*Alley et al.*, 1997; *Ellison et al.*, 2006; *LeGrande et al.*, 2006; *Came et al.*, 2007], which would only reduce the U/Ca signal. Therefore, we interpret the changes in U/Ca (Figure 2) as reflecting changes in the estuary geochemistry, with any carbonate ion and temperature changes only reducing the measured signal.

[9] Our U/Ca records thus support the hypothesis of routing of western Canadian Plains runoff through Hudson Strait concurrent with the collapse of ice over Hudson Bay ~8.47 ka [*Barber et al.*, 1999; *Licciardi et al.*, 1999; *Clark et al.*, 2001]. Unfortunately, we are not able to directly date the subsequent reduction in U/Ca because of the limited amount of available carbonate material in the sediments. However, linear interpolation between the age of the routing onset ~8.47 ka in core 002 (145 cm depth) [*Barber et al.*,

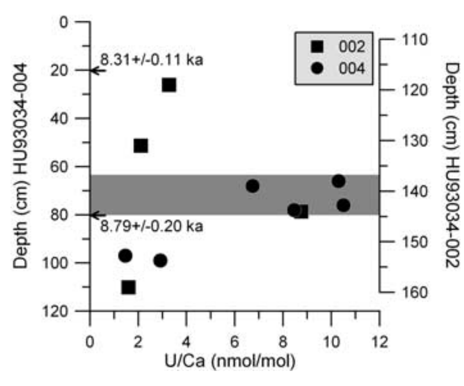

Figure 2. U/Ca records from Hudson Strait on depth scale. The HU93034-004 record (circle symbols) depth scale is on the left with the two closest calibrated radiocarbon dates denoted by arrows (Table S2). The HU93034-002 record (square symbols) depth scale is on the right. The gray bar shows the interval in both cores that follows the opening of Hudson Bay based on magnetic susceptibility and faunal assemblages [*Kerwin*, 1996; *Jennings et al.*, 1998, 2001; *Barber et al.*, 1999; *MacLean et al.*, 2001].

1999] and the radiocarbon date at 4 cm depth (~3.75 ka) (Table S1) [*Jennings et al.*, 1998] suggests that the reduction in U/Ca and the inferred reduction in western Canadian Plains runoff through Hudson Strait occurred ~8 ka. In any event, rerouting of western Canadian Plains runoff away from Hudson Bay may have occurred in association with rapid ongoing isostatic rebound of the drainage divide between the western Canadian Plains and the Canadian Shield, establishing the current northwestward drainage into the Mackenzie River.

3. Modeling the Change in Freshwater Runoff

[10] We use an estuary geochemical mixing model [*Carlson et al.*, 2007] to determine the changes in runoff associated with the ~7 nmol/mol increase in foraminifera U/Ca following the opening of Hudson Bay. We model the changes in estuary U and Ca concentration as:

$$I_{e-x} = \frac{F_{r-x} I_{r-x} + F_o I_o}{F_{r-x} + F_o}, \tag{1}$$

where F_{r-x} and I_{r-x} are the runoff flux (Sv) and runoff concentration (mol l^{-1}) of a given element (U or Ca), respectively, at time x ($x = 1$ for pre-Hudson Bay opening, $x = 2$ for open Hudson Bay). F_o and I_o are the ocean flux (Sv) and ocean concentration (mol l^{-1}) of a given element, respectively, and I_{e-x} is the concentration (mol l^{-1}) of the element in the estuary at time x. We then determine the change in estuary chemistry (ΔI) for a given element:

$$\Delta I = I_{e-2} - I_{e-1}. \tag{2}$$

F_{r-2} is tuned so that ΔI matches the observed change in foraminfera U/Ca after accounting for the offset between U/Ca of the test relative to U/Ca of ocean water [*Russell et al.*, 1994]. The change in F_{r-2} relative to F_{r-1} is then taken as the change in freshwater discharge due to the routing of western Canadian Plains runoff through Hudson Strait.

[11] For Eqn. 1, we use the ocean concentration (I_o) of U and Ca [*Pilson*, 1998] scaled to the salinity of the in-flowing ocean water to Hudson Strait [*Drinkwater*, 1986; *Straneo and Saucier*, 2008], and an ocean water flux (F_o) of 0.9 Sv into Hudson Strait [*Drinkwater*, 1986; *Straneo and Saucier*, 2008]. For the river element concentrations, we assume the average concentration of U and Ca in western Canadian Plains river water of 1.01×10^{-8} mol l^{-1} and 1.00×10^{-3} mol l^{-1}, respectively, determined by the Saskatchewan Watershed Authority. U does not behave conservatively in estuary environments like Ca, however, and is released from colloids and particulates at salinities >20 practical salinity units (psu) [*Swarzenski et al.*, 2003]. Similar to our previous work [*Carlson et al.*, 2007], we model this effect using a maximum U release from colloids and particulates of 245% (Z, %) at a discharge (F_r, Sv) of 0.2 Sv [*Swarzenski et al.*, 2003]:

$$Z = 0.579 \exp(7.66 F_r). \tag{3}$$

We also assume a runoff discharge (F_r) prior to the opening of Hudson Bay ($x = 1$) of 0.055 Sv [*Licciardi et al.*, 1999] that is dilute in U and Ca (direct melting of ice surrounding Hudson Bay with minimal bedrock contact; Figure 1).

[12] Results from our estuary geochemical mixing model indicate that an increase in freshwater runoff of ~0.13 Sv from the Western Canadian Plains would explain the ~7 nmol/mol increase in foraminifera U/Ca following the opening of Hudson Bay. With the variability in U/Ca both before (±0.8 nmol/mol) and during the routing event (±1.5 nmol/mol), we calculate a discharge error of ±0.03 Sv. We note that our geochemical-based 0.13 ± 0.03 Sv runoff increase is in agreement with an increase of ~0.12 Sv estimated from an ice sheet/atmospheric general circulation model [*Licciardi et al.*, 1999].

4. Implications for Atlantic Meridional Overturning Circulation

[13] Our geochemical records and modeling results indicate that the routing of western Canadian Plains runoff through Hudson Strait provided a sustained freshwater flux of ~0.13 Sv to the Labrador Sea in addition to the much larger (~5 Sv) but significantly shorter-lived (~0.5-year) flood from the drainage of glacial Lake Agassiz [*Clarke et al.*, 2004]. Fully coupled atmosphere-ocean general circulation models (AOGCMs) simulate an ~30% reduction in AMOC strength in response to a 0.1 Sv forcing with the length of the AMOC reduction controlled by the length of the freshwater forcing [*Stouffer et al.*, 2006]. In contrast, a 2.5–5 Sv, 0.5–1 year flood causes an ~40% reduction in AMOC for 20–30 years in one fully coupled AOGCM, with the climate anomalies persisting for <40 years [*LeGrande et al.*, 2006; *LeGrande and Schmidt*, 2008]. *Meissner and Clark* [2006] found similar differences in the AMOC response to short-lived floods and sustained routing events in simulations with an earth-systems model of intermediate complexity. Simulations with another AOGCM, on the other hand, indicate negligible response of the AMOC to the flood and routing event, although sustained climate anomalies developed in response to the decrease in sea surface salinity and attendant increase in sea ice production [*Clarke et al.*, 2009].

[14] These different AMOC responses to a large but brief flood relative to a sustained yet considerably smaller routing event suggest that there may be multiple AMOC responses to the opening of Hudson Bay and the attendant flood and routing event. Indeed, a high-resolution benthic δ^{13}C record from the southeastern Labrador Sea (MD03-2665, Figure 1) suggests the presence of Southern Ocean-sourced bottom water (low δ^{13}C) ~8.32 ka for a period of ~70 years (Figure 3c) [*Kleiven et al.*, 2008]. Another high-resolution proxy of AMOC strength (mean sortable silt) from the Gardar Drift (MD99-2251, Figure 1) shows decreased mean silt size suggesting reduced AMOC strength ~8.5–8.0 ka with a minimum at ~8.27 ka (Figure 3b) [*Ellison et al.*, 2006]. Although the rapid drainage of glacial Lake Agassiz 8.47 ± 0.2 ka, or shortly thereafter, may have caused the decades-long minimum in AMOC strength ~8.3 ka [*Ellison et al.*, 2006; *Kleiven et al.*, 2008], we also propose that the centuries-long freshwater discharge from the routing of western Canadian Plains runoff induced the extended reduction in AMOC strength ~8.5–8.0 ka (Figure 3). This longer freshwater forcing and its effects on the AMOC may

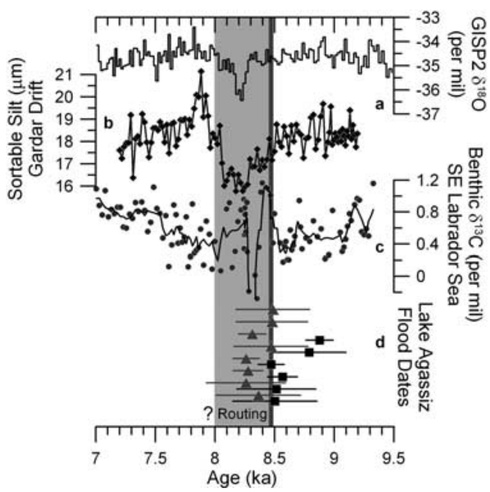

Figure 3. Lake drainage, routing, Atlantic meridional overturning and climate. (a) GISP2 δ^{18}O [*Alley et al.*, 1997]. (b) Sortable silt from the Gardar Drift (black diamonds) (Figure 1) [*Ellison et al.*, 2006]. (c) Benthic δ^{13}C from the southeast Labrador Sea (gray circles with 5-point running average) (Figure 1) [*Kleiven et al.*, 2008]. (d) Reservoir corrected and calibrated (CALIB 5.0.2) [*Stuiver et al.*, 1998] radiocarbon dates from prior to the opening of Hudson Bay (black squares) and after the opening of Hudson Bay (gray triangles) with 2-sigma error bars [*Barber et al.*, 1999]. Dark gray bar denotes best estimate for the drainage of glacial Lake Agassiz, noting that the timing of lake drainage is likely younger than indicated as the reservoir correction for Hudson Bay is a conservative estimate [*Barber et al.*, 1999]. Light gray bar denotes routing of Western Canadian Plains runoff, though the actual duration is not well constrained.

explain the multi-centennial climate anomalies that have been correlated to the 8.2 ka cold event [e.g., *Alley and Ágústdóttir*, 2005; *Rohling and Pälike*, 2005].

[15] **Acknowledgments.** We thank A. Ungerer for help with the ICP-MS, J. Padman and M. Cheseby for help with foraminifera identification, A. Jennings for discussion of core fauna and stratigraphy, the Saskatchewan Watershed Authority for river chemistry data, H. Kleiven for data from the Eirik Drift, and the Bedford Institute of Oceanography for the core samples. Comments by two reviewers improved this manuscript. This research was supported by the University of Wisconsin-Madison start-up funds (A. Carlson) and the National Science Foundation (A. Carlson, P. Clark, G. Klinkhammer).

References

Alley, R. B., and A. M. Ágústdóttir (2005), The 8k event: Cause and consequences of a major Holocene abrupt climate change, *Quat. Sci. Rev.*, *24*, 1123–1149, doi:10.1016/j.quascirev.2004.12.004.

Alley, R. B., et al. (1997), Holocene climatic instability: A prominent, widespread event 8200 yr ago, *Geology*, *25*, 483–486, doi:10.1130/0091-7613(1997)025<0483:HCIAPW>2.3.CO;2.

Barber, D. C., et al. (1999), Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, *400*, 344–348, doi:10.1038/22504.

Came, R. E., D. W. Oppo, and J. F. McManus (2007), Amplitude and timing of temperature and salinity variability in the subpolar North Atlantic over the past 10 k.y., *Geology*, *35*, 315–318, doi:10.1130/G23455A.1.

Carlson, A. E., et al. (2007), Geochemical proxies of North American freshwater routing during the Younger Dryas cold event, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 6556–6561, doi:10.1073/pnas.0611313104.

Clark, P. U., et al. (2001), Freshwater forcing of abrupt climate change during the last glaciation, *Science*, *293*, 283–287, doi:10.1126/science.1062517.

Clarke, G. K. C., D. W. Leverington, J. T. Teller, and A. S. Dyke (2004), Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event, *Quat. Sci. Rev.*, *23*, 389–407, doi:10.1016/j.quascirev.2003.06.004.

Clarke, G. K. C., A. B. G. Bush, and J. W. M. Bush (2009), Freshwater discharge, sediment transport, and modeled climate impacts of the final drainage of glacial Lake Agassiz, *J. Clim.*, *22*, 2161–2180, doi:10.1175/2008JCLI2439.1.

Drinkwater, K. F. (1986), Physical oceanography of Hudson Strait and Ungava Bay, in *Canadian Inland Seas*, *Elsevier Oceanogr. Ser.*, vol. 44, edited by I. P. Martini, pp. 237–264, Elsevier, Amsterdam.

Dyke, A. S. (2004), An outline of North American deglaciation with emphasis on central and northern Canada, in *Quaternary Glaciations: Extent and Chronology II*, edited by J. Ehlers and P. L. Gibbard, pp. 373–424, Elsevier, Amsterdam.

Ellison, C. R. W., M. R. Chapman, and I. R. Hall (2006), Surface and deep ocean interactions during the cold climate event 8200 years ago, *Science*, *312*, 1929–1932, doi:10.1126/science.1127213.

Haley, B. A., and G. P. Klinkhammer (2002), Development of a flow-through system for cleaning and dissolving foraminiferal tests, *Chem. Geol.*, *185*, 51–69, doi:10.1016/S0009-2541(01)00399-0.

Hilbrecht, H. (1996), Extant planktonic foraminifera and the physical environment in the Atlantic and Indian oceans, *Neue Folge. 300*, Mitteilungen aus dem Geol. Inst. der Eidgen, Tech. Hochschule und der Univ. Zürich, Zurich, Austria.

Jennings, A. E., W. F. Manley, B. MacLean, and J. T. Andrews (1998), Marine evidence for the last glacial advance across eastern Hudson Strait, eastern Canadian Arctic, *J. Quat. Sci.*, *13*, 501–514, doi:10.1002/(SICI)1099-1417(1998110)13:6<501::AID-JQS391>3.0.CO;2-A.

Jennings, A. E., G. Vilks, B. Deonarine, A. Silis, and N. Weiner (2001), Foraminiferal biostratigraphy and paleoceanography, in *Marine Geology of Hudson Strait and Ungava Bay, Eastern Arctic Canada: Late Quaternary Sediments, Depositional Environments, and Late Glacial-Deglacial History Derived From Marine and Terrestrial Studies*, edited by B. MacLean, *Geol. Surv. Can. Bull.*, 566, 127–146.

Kerwin, M. W. (1996), A regional stratigraphic isochron (ca. 8000 ^{14}C yr B.P.) from final deglaciation of Hudson Strait, *Quat. Res.*, *46*, 89–98, doi:10.1006/qres.1996.0049.

Kleiven, H. F., et al. (2008), Reduced North Atlantic Deep Water coeval with the glacial Lake Agassiz freshwater outburst, *Science*, *319*, 60–64, doi:10.1126/science.1148924.

LeGrande, A. N., and G. A. Schmidt (2008), Ensemble, water isotope-enabled, coupled general circulation modeling insights into the 8.2 ka event, *Paleoceanography*, *23*, PA3207, doi:10.1029/2008PA001610.

LeGrande, A. N., et al. (2006), Consistent simulations of multiple proxy responses to an abrupt climate change event, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 837–842, doi:10.1073/pnas.0510095103.

Licciardi, J. M., J. T. Teller, and P. U. Clark (1999), Freshwater routing by the Laurentide ice sheet during the last deglaciation, in *Mechanisms of Global Climate Change at Millennial Time Scales*, *Geophys. Monogr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, pp. 177–201, AGU, Washington, D. C.

MacLean, B., et al. (2001), Hudson Strait Quaternary sediments and late glacial and deglaciation history: A discussion and summary, in *Marine Geology of Hudson Strait and Ungava Bay, Eastern Arctic Canada: Late Quaternary Sediments, Depositional Environments, and Late Glacial-Deglacial History Derived From Marine and Terrestrial Studies*, edited by B. MacLean, *Geol. Surv. Can. Bull.*, 566, 181–191.

Meissner, K. J., and P. U. Clark (2006), Impact of floods versus routing events on the thermohaline circulation, *Geophys. Res. Lett.*, *33*, L15704, doi:10.1029/2006GL026705.

Meybeck, M. (1987), Global chemical weathering of surficial rocks estimated from river dissolved loads, *Am. J. Sci.*, *287*, 401–428.

Palmer, M. R., and J. M. Edmond (1993), Uranium in river water, *Geochim. Cosmochim. Acta*, *57*, 4947–4955, doi:10.1016/0016-7037(93)90131-F.

Pilson, M. E. Q. (1998), *An Introduction to the Chemistry of the Sea*, Prentice Hall, Upper Saddle River, N. J.

Rohling, E. J., and H. Pälike (2005), Centennial-scale climate cooling with a sudden cold event around 8,200 years ago, *Nature*, *434*, 975–979, doi:10.1038/nature03421.

Russell, A. D., S. Emerson, B. K. Nelson, J. Erez, and D. W. Lea (1994), Uranium in foraminiferal calcite as a recorder of seawater uranium concentrations, *Geochim. Cosmochim. Acta*, *58*, 671–681, doi:10.1016/0016-7037(94)90497-9.

Russell, A. D., B. Hönisch, H. J. Spero, and D. W. Lea (2004), Effects of seawater carbonate ion concentration and temperature on shell U, Mg, and Sr in cultured planktonic foraminifera, *Geochim. Cosmochim. Acta*, *68*, 4347–4361, doi:10.1016/j.gca.2004.03.013.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*, 1365–1387, doi:10.1175/JCLI3689.1.

Straneo, F., and F. Saucier (2008), The outflow from Hudson Strait and its contribution to the Labrador Current, *Deep Sea Res., Part I*, *55*, 926–946, doi:10.1016/j.dsr.2008.03.012.

Stuiver, M., et al. (1998), INTCAL98 radiocarbon age calibration, 24000–0 cal B.P., *Radiocarbon*, *40*, 1041–1083.

Swarzenski, P. W., D. Porcelli, P. S. Andersson, and J. M. Smoak (2003), The behavior of U- and Th-series nuclides in the estuarine environment, *Rev. Mineral. Geochem.*, *52*, 577–606, doi:10.2113/0520577.

Thomas, E. R., et al. (2007), The 8.2 ka event from Greenland ice cores, *Quat. Sci. Rev.*, *26*, 70–81, doi:10.1016/j.quascirev.2006.07.017.

Yu, J., H. Elderfield, Z. Jin, and L. Booth (2008), A strong temperature effect on U/Ca in planktonic foraminiferal carbonates, *Geochim. Cosmochim. Acta*, *72*, 4988–5000, doi:10.1016/j.gca.2008.07.011.

A. E. Carlson, Deptartment of Geology and Geophysics, University of Wisconsin-Madison, 1215 West Dayton Street, Madison, WI 53706, USA. (acarlson@geology.wisc.edu)

P. U. Clark, Department of Geosciences, Oregon State University, 104 Wilkinson Hall, Corvallis, OR 97331, USA.

B. A. Haley, Leibniz Institute of Marine Sciences, University of Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany.

G. P. Klinkhammer, College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Admin Building, Corvallis, OR 7331, USA.