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Origin of the first global meltwater pulse following the last glacial maximum

Peter U. Clark,[1] Richard B. Alley,[2] Lloyd D. Keigwin,[3] Joseph M. Licciardi,[1]
Sigfus J. Johnsen,[4,5] and Huaxiao Wang[6]

Abstract. Well-dated sea level records show that the glacioeustatic rise following the last glacial maximum was characterized by two or possibly three brief intervals of rapid sea level rise separating periods with much lower rates. These very high rates of sea level rise indicate periods of exceptionally rapid deglaciation of remaining ice sheets. The Laurentide Ice Sheet is commonly targeted as the source of the first, and largest, of the meltwater pulses (mwp-IA between ~14,200 (12,200 ^{14}C years B.P.) and 13,700 years ago (11,700 ^{14}C years B.P.)). In all oceanic records of deglaciation of the former northern hemisphere ice sheets that we review, only those from the Gulf of Mexico and the Bermuda Rise show evidence of low δ^{18}O values at the time of mwp-IA, identifying the southern Laurentide Ice Sheet as a potential source for mwp-IA. We question this source for mwp-IA, however, because (1) ice sheet models suggest that this sector of the ice sheet contributed only a fraction (<10%) of the sea level needed for mwp-IA, (2) melting this sector of the ice sheet at the necessary rate to explain mwp-IA is physically implausible, and (3) ocean models predict a much stronger thermohaline response to the inferred freshwater pulse out of the Mississippi River into the North Atlantic than is recorded. This leaves the Antarctic Ice Sheet as the only other ice sheet capable of delivering enough sea level to explain mwp-IA, but there are currently no well-dated high-resolution records to document this hypothesis. These conclusions suggest that reconstructions of the Laurentide Ice Sheet in the ICE-4G model, which are constrained to match the sea level record, may be too low for time periods younger than 15,000 years ago. Furthermore, δ^{18}O records from the Gulf of Mexico show variable fluxes of meltwater from the southern margin of the Laurentide Ice Sheet which can be traced to the opening and closing of eastward draining glacial-lake outlets associated with surging ice sheet behavior. These variable fluxes through eastern outlets were apparently sufficient to affect formation of North Atlantic Deep Water, thus underscoring the sensitivity of this process to changes in freshwater forcing.

Introduction

Well-dated sea level records show that the glacioeustatic rise following the last glacial maximum (approximately 21,000 years ago) (calendar years are represented as years and radiocarbon years are represented as ^{14}C years B.P.) was characterized by two or possibly three brief intervals of rapid sea level rise separating periods with much lower rates (Figure 1) [*Fairbanks*, 1989; *Bard et al.*, 1990a; *Edwards et al.*, 1993; *Blanchon and Shaw*, 1995]. These very high rates of sea level rise indicate periods of exceptionally rapid deglaciation of remaining ice sheets. The source(s) of these rapid rates of sea level rise, or "meltwater pulses" [*Fairbanks*, 1989], however, has not been established. In the case of the first, and largest, of the meltwater pulses, several different ice sheets have been implicated. The Fennoscandian Ice Sheet may have been responsible [*Birchfield et al.*, 1994] because it occurs "downwind" of the Nordic seas where large amounts of heat are released when active in the formation of North Atlantic Deep Water (NADW). The Barents Ice Sheet may have been responsible because it was largely grounded below sea level and therefore susceptible to the rapid collapse suggested by the first meltwater pulse [*Lindstrom and MacAyeal*, 1993]. Many researchers, however, have targeted the Laurentide Ice Sheet as the primary source for the first meltwater pulse for two reasons: (1) The Laurentide was the largest ice sheet and thus most likely to deliver such a large volume of meltwater, and (2) oxygen isotopes in deep-sea cores from the Gulf of Mexico and midlatitude North Atlantic record an interval of low δ^{18}O at the time of the first meltwater pulse suggesting that glacial meltwater discharged down the Mississippi River and spread as a low-salinity plume

[1]Department of Geosciences, Oregon State University, Corvallis.
[2]Earth System Science Center and Department of Geosciences, Pennsylvania State University, University Park.
[3]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.
[4]Niehls Bohr Institute, Department of Geophysics, University of Copenhagen, Denmark.
[5]Also at Science Institute, Department of Geophysics, University of Iceland, Reykjavik.
[6]Lawrence Livermore National Laboratory, Livermore, California.

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across the temperate North Atlantic [e.g., *Keigwin et al.*, 1991; *Charles and Fairbanks*, 1992; *Fairbanks et al.*, 1992; *Lehman and Keigwin*, 1992]. This interpretation has figured prominently in recent modeling of the deglaciation of the global ice sheets (ICE-4G) [*Peltier*, 1994], whereby the Laurentide Ice Sheet is constrained to lose nearly 20 m of sea level equivalent during the first meltwater pulse between 15,000 and 14,000 years ago.

In this paper, we present several lines of evidence which suggest that the Laurentide Ice Sheet could not have been the primary contributor to this first meltwater pulse. Although $\delta^{18}O$ records clearly identify meltwater flowing down the Mississippi River, our evidence suggests that this discharge likely only accounted for a fraction of the total sea level rise. Furthermore, deep-sea records of meltwater and iceberg discharge from the Gulf of St. Lawrence and Hudson Strait, or areas that served as the other primary outlets of freshwater to the North Atlantic in addition to the Mississippi River, show evidence of significantly reduced discharge at the time of the first meltwater pulse. Because marine records near the former Fennoscandian and Barents Ice Sheets also show no signature of accelerated deglaciation at the time of the first meltwater pulse, records of deglaciation of the Antarctic Ice Sheet should be examined for possible evidence of its role in this prominent sea level event.

Sea Level Record

Assuming a 105 m rise of global sea level between 21,000 and 6000 years ago [*Peltier*, 1994], the rate of sea level rise would be 7 m/1000 years if all ice sheets had melted uniformly. Corals dated by U/Th recording sea level rise at Barbados [*Fairbanks*, 1989; *Bard et al.*, 1990a, 1993], New Guinea [*Edwards et al.*, 1993], and Tahiti [*Bard et al.*, 1995], however, show that between 15,000 and 10,000 years ago, the postglacial sea level history was punctuated by two brief intervals of rapid rates of sea level rise, which *Fairbanks* [1989] referred to as meltwater pulses (mwp's) IA and IB (Figure 1). According to the Barbados record, sea level during the first meltwater pulse (mwp-IA) rose about 24 m between 14,690 $\pm$ 25 years ago (12,600 $\pm$ 460 ^{14}C years B.P.) and 13,730 $\pm$ 100 years ago (11.720 + 400 ^{14}C years B.P.), with most of this sea level rise (19 m) occurring after 14,230 $\pm$ 100 years (12,200 $\pm$ ^{14}C years B.P.) [*Bard et al.*, 1990a] (Figure 1; Table 1). *Blanchon and Shaw* [1995] argued that changes from a monospecific *Acropora palmata* reef framework to a deeper-water coral reef framework constrain 13.5 m of sea level rise in <290 $\pm$ 50 years beginning at or shortly after 14,230 $\pm$ 100 years ago. On the basis of this estimate, meltwater was introduced to the global oceans during mwp-IA at an average rate of ~4.5 cm/yr, corresponding to a freshwater flux of ~0.52 Sv (Sverdrup) (1 Sv = 10^6 m^3 s^{-1}), for about 300 years. The Fairbanks and Bard data give a best-estimate sea level rise of 19 m over 500 years (3.8 cm/yr), or 0.43 Sv. Thus the freshwater flux of mwp-IA is in the vicinity of 0.5 Sv by either calculation, while the estimate of sea level rise ranges from 13.5 to 19 m.

Evidence From Northern Hemisphere Ice Sheets

The rapidity and magnitude of mwp-IA strongly suggests abrupt collapse of some portion(s) of remaining ice sheets. If the northern hemisphere ice sheets were involved, this event should have left a clear signal in the North Atlantic Ocean, which received most of the meltwater and icebergs from these ice sheets. Here we examine records for evidence of an abrupt deglaciation event from the northern hemisphere ice sheets at the time of mwp-IA.

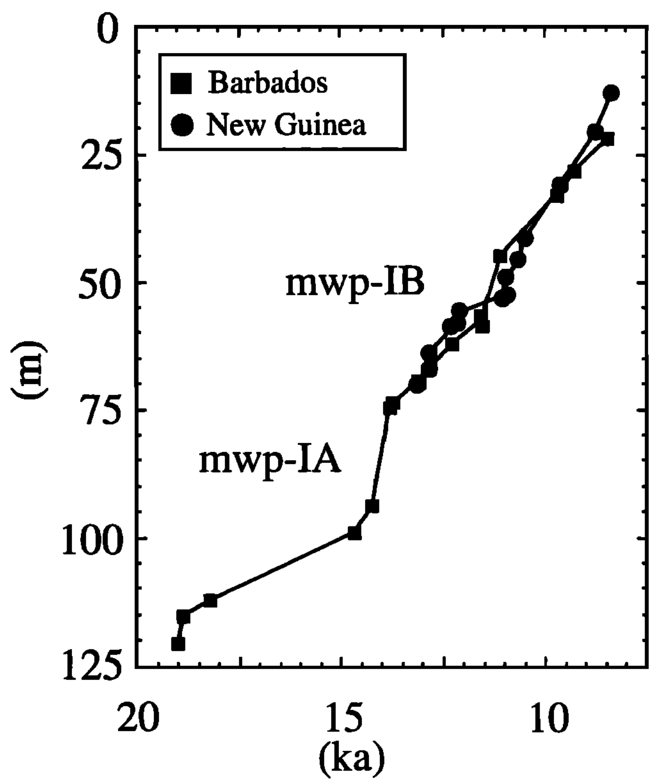

Figure 1. Coral records of sea level dated by U/Th from Barbados [*Bard et al.*, 1990a, 1993] and New Guinea [*Edwards et al.*, 1993]. Two periods of rapid rise of sea level are identified as mwp-IA and mwp-IB.

Laurentide Ice Sheet

The Laurentide Ice Sheet was the largest of the former ice sheets. Most meltwater and icebergs from the Laurentide Ice Sheet drained to the North Atlantic through three outlets: Hudson Strait, the Gulf of St. Lawrence, and the Mississippi River (Figure 2). The oxygen isotope record in both the Gulf of Mexico [*Leventer et al.*, 1982] and the Bermuda Rise [*Keigwin et al.*, 1991] show a spike of low $\delta^{18}O$ at the time of mwp-IA (Figure 3b), leading several researchers to suggest that the meltwater pulse originated from the southern margin of the Laurentide Ice Sheet through the Mississippi River to the Gulf of Mexico [*Keigwin et al.*, 1991; *Fairbanks et al.*, 1992] [see also *Emiliani*, 1976; *Emiliani et al.*, 1978].

Extracting a meltwater flux of 0.5 Sv from the 2 x 10^{12} m^2 or less sector of the Laurentide Ice Sheet draining to the Gulf of Mexico would require that the entire sector became an ablation

Table 1. Ages of Samples Constraining the Timing of Meltwater Pulse IA

Sample	Depth, [a] m	U/Th, [b] years (at 2 σ)	^{14}C, [b] years B.P. (at 2 σ)
RGF12-21-10	-70	13,730 ± 100 (2)	11,720 ± 400 (1)
RGF9-8-2	-89	14,230 ± 100 (1)	12,200 ± 75 (2)
RGF9-13-3	-94	14,690 ± 25 (2)	12,600 ± 460 (3)

[a] Depths are relative to the present sea level and can be converted to former sea level by multiplying by the average long-term uplift rate of Barbados (0.34 m/1000 years) [*Fairbanks*, 1989].
[b] Ages are weighted means if more than one age determination was measured on same sample. Number of age determinations are shown by numbers in parentheses. Data from *Fairbanks* [1989] and *Bard et al.* [1990a, 1993].

zone with an average melt rate of at least 8 m/yr of ice, an extreme rate for any ice on Earth at present and an implausibly high rate for a large section of an ice sheet [cf. *Andrews*, 1973]. Estimates of the temperature sensitivity of melting of the modern Greenland Ice Sheet, when scaled to the area of the Mississippi sector, produce an annual average meltwater increase of 0.004-0.007 Sv/degree warming if snowfall does not increase and somewhat less if snowfall does increase [*Warrick and Oerlemans*, 1990]. This suggests that an increase of 0.5 Sv in meltwater from the Mississippi drainage could be achieved for a 1° warming if that part of the Laurentide were at least 70-125 times more sensitive to warming than the modern Greenland Ice Sheet, by a warming of 70°-125° with modern Greenland sensitivity, or by some combination of increased warming and sensitivity. None of these seems physically plausible, and they would be even less plausible if we considered only a seasonal melt rate.

Numerical modeling of the Laurentide Ice Sheet provides estimates of the ice volume contained within the sector of the ice sheet that drained to the Mississippi River. Using ice sheet reconstructions by *Hughes* [1987], *Teller* [1990] estimated the volume of runoff to the Mississippi River derived from precipitation and ice sheet melting during the last deglaciation. Between 13,000 and 11,000 ^{14}C years B.P., or spanning the interval of mwp-IA [*Fairbanks*, 1989] (Table 1), the component of runoff to the Gulf of Mexico from glacial meltwater alone ranged between 0.02 to 0.04 Sv, suggesting discharges more than an order of magnitude lower than those needed to explain mwp-IA [*Teller*, 1990].

We reconstructed the Laurentide Ice Sheet during the last deglaciation (Figure 4) (J.M. Licciardi et al., Modeling the Laurentide Ice Sheet through the last deglaciation, submitted to *Quaternary Science Reviews*, 1996 (hereinafter referred to as J.M. Licciardi et al., submitted manuscript, 1996)) using a numerical model that includes the effects of subglacial sediment deformation on ice flow [*Clark et al.*, 1996; *Jenson et al.*, 1995, 1996]. Like *Teller*'s [1990] results using ice sheet reconstructions by *Hughes* [1987], our reconstructions also suggest that the sector of the ice sheet supplying meltwater to the Gulf of Mexico contained only a fraction of the ice volume required to explain mwp-IA. Between 12,000 and 11,000 ^{14}C years B.P., the decrease in ice volume in the sector of the ice sheet draining to the Mississippi River would have increased global sea level by 2.9 m, equivalent to a meltwater flux of 0.03 Sv over that time, similar to estimates made by *Teller* [1990].

We thus conclude that it is physically implausible to melt the volume of ice from the Mississippi sector of the Laurentide Ice Sheet within the time suggested by mwp-IA and that the volume of meltwater that flowed down the Mississippi River, suggested by ice sheet models, was only a fraction (<10%) of the flux required to explain the sea level rise during this interval [cf. *Andrews*, 1976].

We next examined records of meltwater and iceberg discharge through Hudson Strait and the Gulf of St. Lawrence, as these represent two other primary outlets of meltwater and icebergs from the Laurentide Ice Sheet to the North Atlantic (Figure 2). Furthermore, these represent more reasonable routes for the rapid collapse of the ice sheet than the Mississippi sector, since the ice sheet could discharge ice directly to the ocean by calving of icebergs.

Large freshwater discharges originating from these outlets are identified by oxygen isotopes and ice-rafted debris (IRD) (Figures 3c and 3d) [*Andrews and Tedesco*, 1992; *Andrews et al.*, 1994; *Bond et al.*, 1992, 1993; *Bond and Lotti*, 1995; *Keigwin and Jones*, 1995]. These data, however, show evidence of only low or reduced discharge of freshwater to the North Atlantic at the time of mwp-IA. Major iceberg-discharge events only occurred out of Hudson Strait (Heinrich events) ~14,500 ^{14}C years B.P. and during the Younger Dryas between 10,000-11,000 ^{14}C years B.P. (Figure 3c) [*Andrews and Tedesco*, 1992; *Hillaire-Marcel et al.*, 1994; *Andrews et al.*, 1995; *Bond and Lotti*, 1995]; these are also the only times of major excursions to light oxygen isotope values [*Andrews et al.*, 1994; *Hillaire-Marcel et al.*, 1994]. At the time of mwp-IA off the coast of Nova Scotia, $\delta^{18}O$ values were at their highest (Figure 3d) and warm-water planktonic foraminifera first became common, suggesting the absence of any significant meltwater out of the Gulf of St. Lawrence at the time of mwp-IA [*Keigwin and Jones*, 1995].

Eurasian Ice Sheets

Marine records of deglaciation of the Fennoscandian and Barents Sea Ice Sheets (Figure 5) show no evidence for a major collapse of these ice sheets during the time of mwp-IA. Oxygen

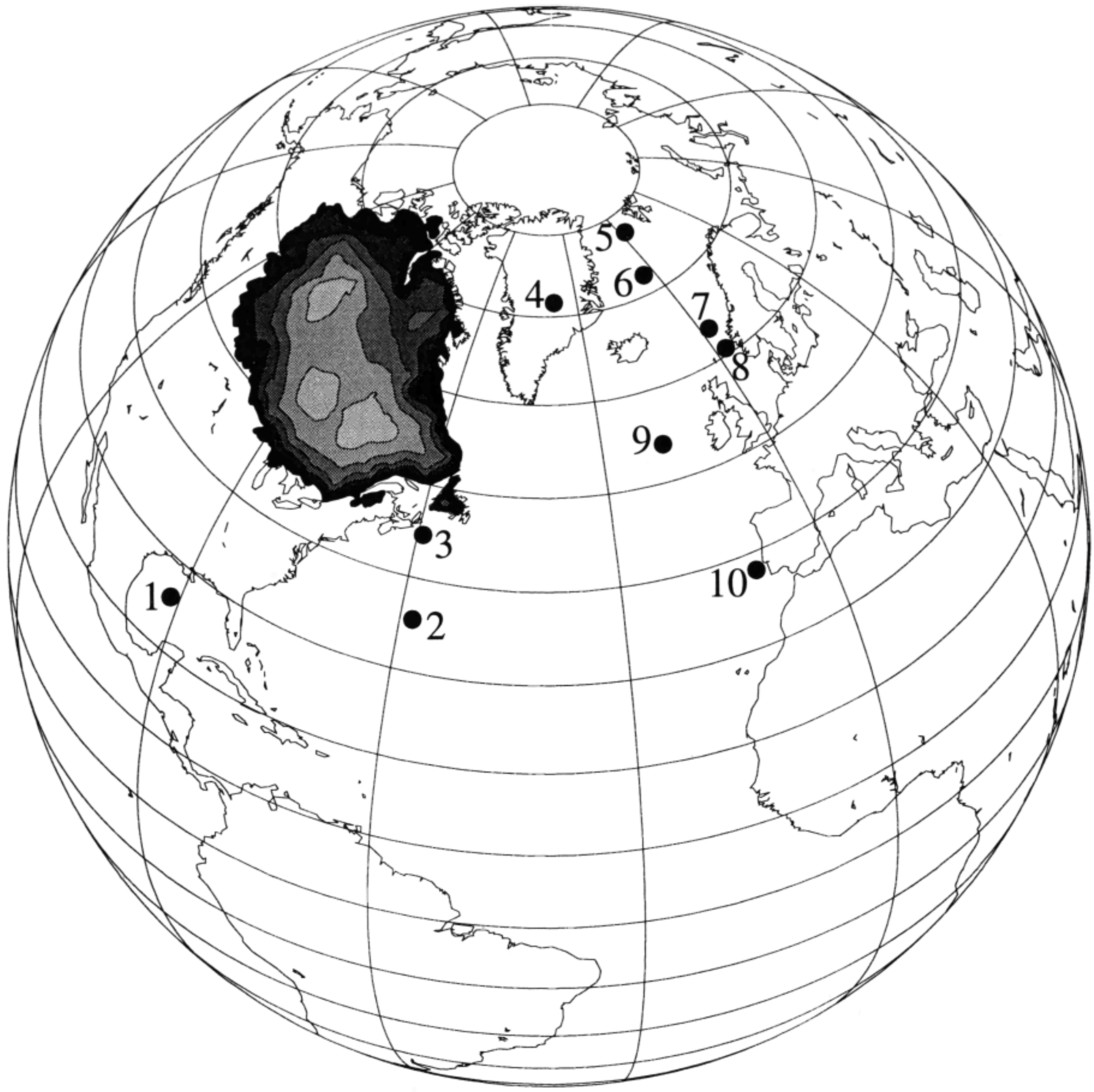

Figure 2. Map showing location of paleoclimate records discussed in the text and showing reconstruction of Laurentide Ice Sheet for 12,000 ^{14}C years B.P. (ice-surface contour interval = 500 m; from J.M. Licciardi et al., submitted manuscript, 1996). Cores are 1, EN32 PC-6; 2, KNR31 GPC5; 3, composite of cores from off the Nova Scotia coast; 4, Summit Greenland ice core; 5, PS21295; 6, HM94-34; 7, HM79 6/4; 8, Troll 3.1; 9, V23-081; and 10, SU81-18.

isotope records from the Norwegian and Greenland Seas (Figures 5b, 5c, 5d, and 5e) and the eastern central Arctic Ocean [*Stein et al.*, 1994] show low δ^{18}O values between 15,000-13,000 ^{14}C years B.P. which are generally attributed to rapid deglaciation of some part of the Eurasian ice sheets [*Jones and Keigwin*, 1988; *Lehman et al.*, 1991; *Koç and Jansen*, 1994], probably the Barents and Kara Sea sectors [*Elverhøi et al.*, 1995; *Polyak et al.*, 1995]. At the time of mwp-IA, however, δ^{18}O values are generally at or near their highest values, suggesting little meltwater input into the Norwegian and Greenland Seas at this time. Reconstructed salinities for the northeastern North Atlantic show comparable trends (Figure 5f), with low values during the early deglaciation of the Eurasian ice sheets and high values comparable to modern values during the time of mwp-IA [*Duplessy et al.*, 1992, 1993].

As further discussed below, these data are consistent with climate records which suggest warm sea surface temperatures and active formation of North Atlantic Deep Water in the Nordic seas at this time [*Karpuz and Jansen*, 1992; *Lehman and Keigwin*, 1992], which would only be expected in the absence of significant freshwater fluxes to these seas, particularly from immediately adjacent (Eurasian) ice sheets.

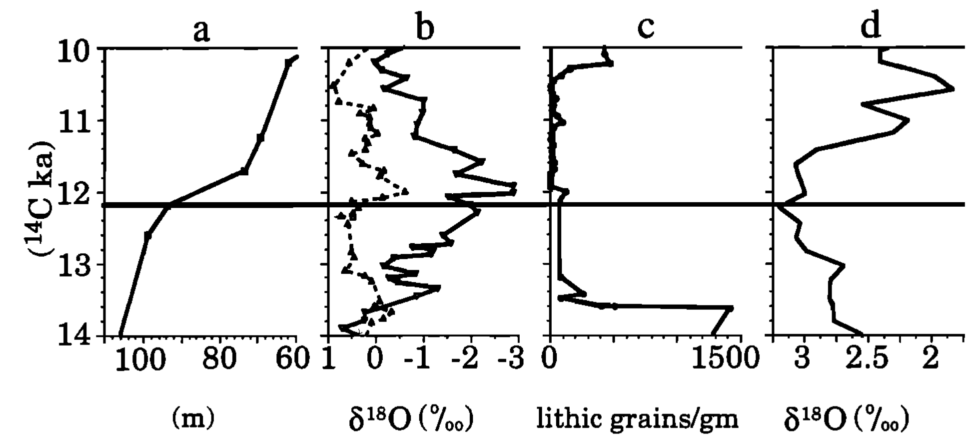

Figure 3. The Barbados sea level record compared with oceanic records of Laurentide Ice Sheet deglaciation between 10,000 and 14,000 ^{14}C years B.P. Solid horizontal line corrresponds to beginning of fastest rate of sea level rise during mwp-IA (see Table 1 for corresponding ages). (a) Barbados sea level record dated by radiocarbon [*Fairbanks*, 1989]. (b) Oxygen isotope records from the Gulf of Mexico (solid line, core EN32 PC-6) (oxygen isotope values from *Leventer et al.* [1982]; age model from *Keigwin et al.* [1991]) and the Bermuda Rise (dashed line, core KNR31 GPC5) [from *Keigwin et al.*, 1991]. Both records measured on planktonic foraminifera *Globigerinoides ruber* (white variety). (c) Record of concentration of lithic grains per gram of sediment from core V23-081 [from *Bond and Lotti*, 1995]. Prominent peak at 13,800-14,000 ^{14}C years B.P. is latter part of Heinrich event 1 and peak from 10,400-10,000 ^{14}C years B.P. is earlier part of Heinrich event 0. (d) Results of stacked oxygen isotope records measured on planktonic foraminifera sinistrally coiled (s.) *Neogloboquadrina pachyderma* from continental slope of Nova Scotia [from *Keigwin and Jones*, 1995].

North Atlantic Deep Water and Climate Change

Formation of North Atlantic Deep Water (NADW) by thermohaline circulation results in significant meridional heat transport into the North Atlantic [*Rooth*, 1982; *Broecker et al.*, 1985]. Geochemical data support the notion that changes in the rate and/or site of formation of NADW and resulting loss of ocean heat transport are associated with abrupt climate change in the North Atlantic region [*Boyle and Keigwin*, 1987; *Keigwin et al.*, 1991; *Lehman and Keigwin*, 1992; *Oppo and Lehman*, 1995]. Ocean models show that formation of NADW is sensitive to any changes in the salinity budget in those areas of deepwater formation. Thus model studies suggest that changes in the rates and sites of formation of NADW may occur by the injection of freshwater to the areas of convection and that NADW formation is more sensitive to high-latitude than low-latitude meltwater discharge [*Bryan*, 1986; *Maier-Reimer and Mikolajewicz*, 1989; *Wright and Stocker*, 1993; *Rahmstorf*, 1994, 1995; *Sakai and Peltier*, 1995].

As summarized above, the only clear signal for enhanced meltwater flux from northern hemisphere ice sheets during the time of mwp-IA is from oxygen isotope records of meltwater flowing down the Mississippi River. Using the Geophysical Fluid Dynamics Laboratory modular ocean model, H. Wang, J.C. Evans, and R.C. Thunell (Thermohaline circulation and meltwater input: OGCM experiments using different surface thermal boundary conditions, submitted to *Journal of Geophysical Research*, 1995 (hereinafter referred to as H. Wang et al., submitted manuscript, 1995)) investigated the effect of meltwater input from the Mississippi River (versus other sources) on thermohaline circulation. Their model results show that a freshwater flux from the Mississippi River of 0.5 Sv results in a >50% reduction in NADW formation within 50 years, and in 150 years, or within the duration of mwp-IA, NADW is nearly completely shut down (Figure 6).

These model results suggest that injection of a flux of freshwater from the Mississippi River equivalent to that suggested by mwp-IA should be accompanied by a major climatic cooling. We thus compared the Barbados sea level record with climate records in order to examine any relation between mwp-IA and climate change.

All climate records show that mwp-IA occurred during the Bølling-Allerød warm interval (Figures 7 and 8). We note, however, that because this warming occurred as a result of intensified formation of NADW in the Nordic seas [*Charles and Fairbanks*, 1992; *Lehman and Keigwin*, 1992], the climatic influence of this process would be largely restricted to the Eurasian ice sheets and would not strongly affect the melting rate of the Laurentide Ice Sheet [*Rind et al.*, 1986; *Manabe and Stouffer*, 1988]. This warming apparently did not have a significant effect on the Eurasian ice sheets either, however, since there is no record of enhanced meltwater discharge to the Greenland and Norwegian Seas during the Bølling-Allerød interval, and in particular during the time of mwp-IA (Figure 5).

All records show a brief cooling interval following the time of mwp-IA, although this cooling is associated with the Older Dryas in the Greenland Ice core Project (GRIP) record (Figure 7c) and with the intra-Allerød cold period in radiocarbon-dated marine records (Figures 8c and 8d) [*Lehman and Keigwin*, 1992]. Geo-

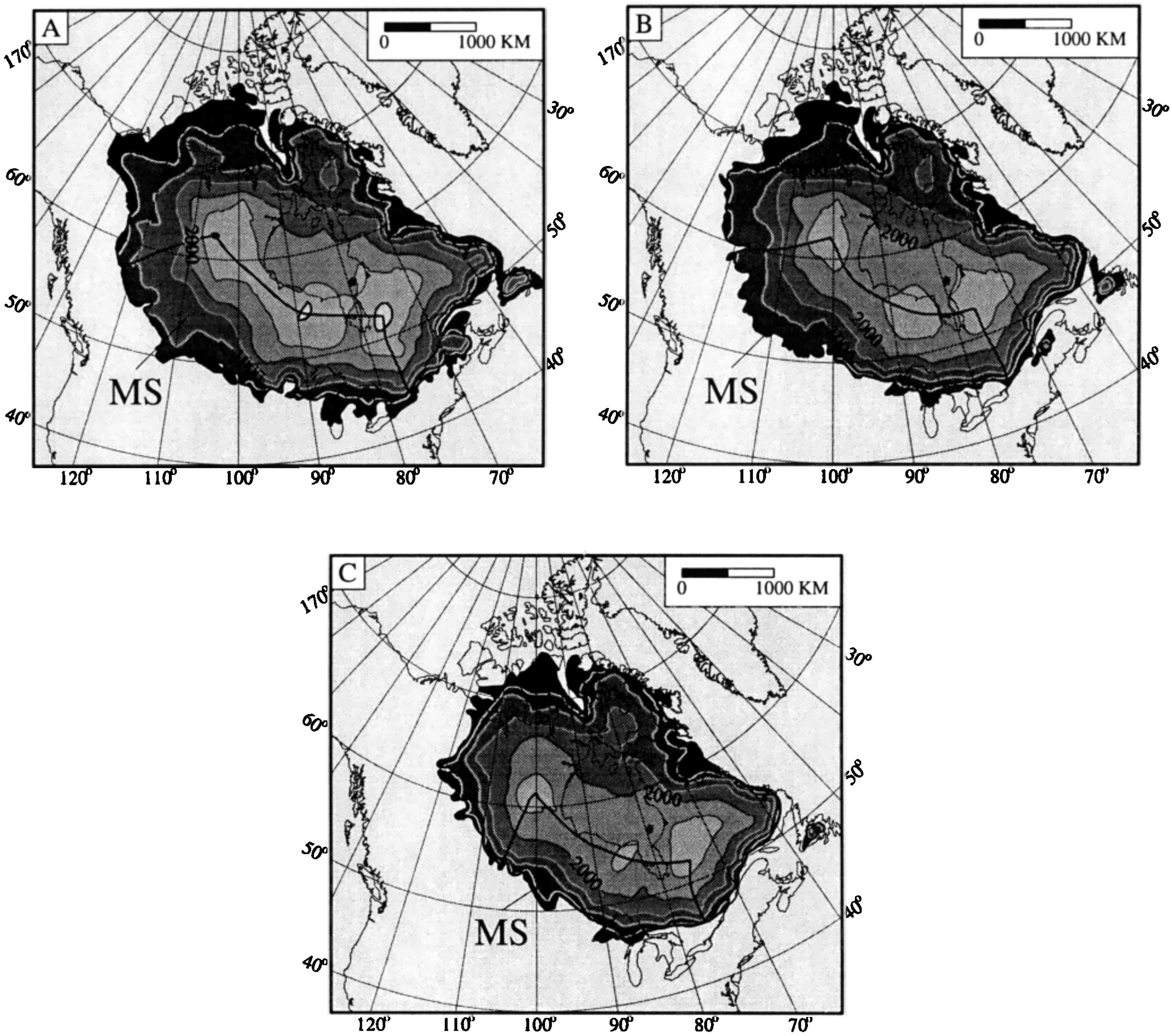

Figure 4. Reconstructions of Laurentide Ice Sheet at (A) 13,000 ^{14}C years B.P., (B) 12,000 ^{14}C years B.P., and (C) 11,000 ^{14}C years B.P. (ice-surface contour interval = 500 m) (from J.M. Licciardi et al., submitted manuscript, 1996). The sector of the ice sheet that drained to the Mississippi River drainage is outlined and labeled MS. These reconstructions and those by *Hughes* [1987] suggest a meltwater flux to the Mississippi drainage of ~0.03 Sv [see also *Teller*, 1990].

chemical data (δ^{13}C, Cd/Ca) also suggest a decrease in the rate of production of NADW following mwp-IA (Figure 8b) [*Keigwin et al.*, 1991; *Charles and Fairbanks*, 1992]. Ocean modeling results (Figure 6) suggest, however, that the effect of a meltwater flux of 0.5 Sv derived from the Mississippi River on NADW production and climate would be significantly greater than the small and short response identified in the climate records. In particular, we contrast the modest climate response following mwp-IA with the greater magnitude and duration of other periods of reduced NADW formation during the last deglaciation [*Keigwin et al.*, 1991; *Keigwin and Lehman*, 1994; *Maslin et al.*, 1995; *Oppo and Lehman*, 1995], despite the observation that these periods occur at times of significantly lower meltwater fluxes than during mwp-IA.

Modeling results by *Sakai and Peltier* [1995] predict that reduction in NADW formation in response to a freshwater forcing of the magnitude suggested by mwp-IA would be significantly delayed from the time of onset of the freshwater event. These results suggest therefore that the Younger Dryas cold event is the observed response to their model prediction and is thus consistent with a source of mwp-IA from the northern hemisphere ice sheets. This model result still requires, however, observational data that identify the northern hemisphere ice sheet(s) as being responsible for mwp-IA which, according to the records we have surveyed, do not exist.

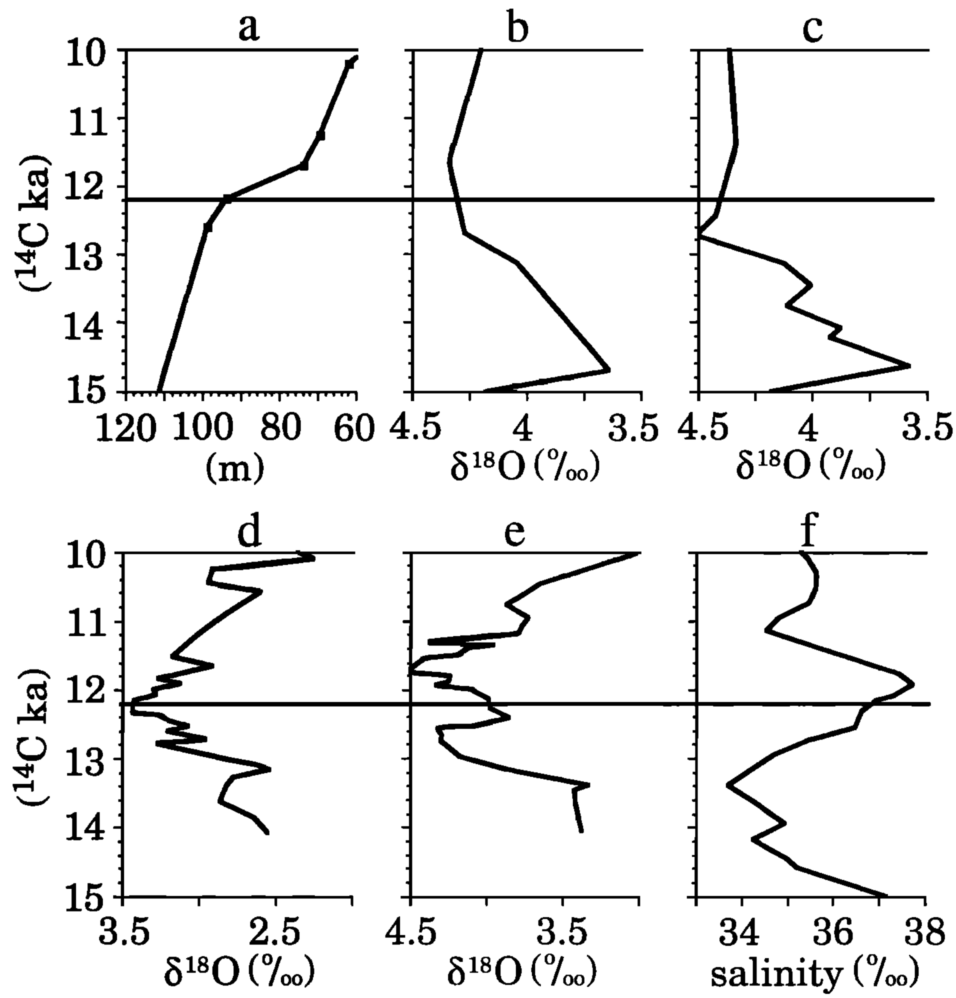

Figure 5. The Barbados sea level record compared with oceanic records that reflect primarily to Eurasian ice sheet deglaciation between 10,000 and 15,000 ^{14}C years B.P. Solid horizontal line corresponds to beginning of fastest rate of sea level rise during mwp-IA (see Table 1 for corresponding ages). (a) Barbados sea level record dated by radiocarbon [*Fairbanks*, 1989]. (b) Oxygen isotope record (core PS21295-4) measured on *N. pachyderma* (s.) from Fram Strait [from *Jones and Keigwin*, 1988]. (c) Oxygen isotope record (core HM94-34) measured on *N. pachyderma* (s.) from the Greenland Basin [from *Koç and Jansen*, 1994]. (d) Oxygen isotope record (core HM79-6/4) measured on *N. pachyderma* (s.) from the continental slope of Norway [from *Karpuz and Jansen*, 1992]. (e) Oxygen isotope record (core Troll 3.1) measured on benthic foraminifera *Nonion labradoricum* before and *Cassidulina laevigata* after 10,500 ^{14}C years B.P. from the continental shelf of Norway [from *Lehman et al.*, 1991]. (f) Reconstructed salinity variations (core SU81-18) off the coast of Portugal [from *Duplessy et al.*, 1993].

Gulf of Mexico Record

Freshwater Fluxes to the Gulf of Mexico and Oxygen Isotope Records

The only clear signal of significant meltwater entering the North Atlantic Ocean at the time of mwp-IA is thus from oxygen isotope records from the Gulf of Mexico, the Bermuda Rise, and the Blake Outer Ridge (Figure 3b) [*Leventer et al.*, 1982; *Haskell et al.*, 1991; *Keigwin et al.*, 1991]. In first examining an oxygen isotope record from the Gulf of Mexico similar to the one discussed here (Figure 3b), *Emiliani et al.* [1978] [see also *Emiliani*, 1976] argued that because the Gulf of Mexico is flushed by the Loop Current of the Gulf Stream with a flux of ~14 Sv [*Schmitz*, 1995], meltwater fluxes of 0.1-0.23 Sv, with peak discharges as high 1 Sv, were required in order to produce the observed 2.4 ‰ isotopic anomaly (compare with Figure 3b). (In making similar arguments, *Emiliani* [1976] initially suggested a freshwater flux as high as 2.4 Sv.)

In responding to discussion of his interpretation of large "floods" down the Mississippi River, *Emiliani* [1976] suggested that those who commented [*Andrews*, 1976; *Farrand and Evenson*, 1976; *Wright and Stein*, 1976] "revisit their tunnel valleys and spillways to look for matching evidence" (p. 1271) from the southern margin of the Laurentide Ice Sheet for these high fluxes. We have revisited the glacial geological record, however, and find no evidence to support a source from the southern Lauren-

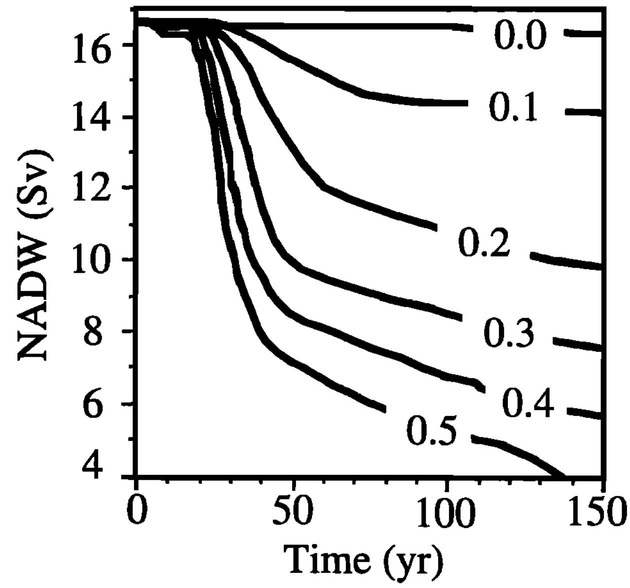

Figure 6. Modeling results of North Atlantic Deep Water production, measured by the maximum of the meridional overturning in the North Atlantic, as a function of the time of integration for different magnitude of freshwater input, under flux boundary conditions (from H. Wang et al., submitted manuscript, 1995). The magnitude of input of freshwater is labeled on each curve in Sverdrup units.

tide Ice Sheet [e.g., *Clayton and Moran*, 1982; *Mickelson et al.*, 1983; *Dyke and Prest*, 1987]. In addition, two independent numerical ice sheet reconstructions [*Hughes*, 1987; J.M. Licciardi et al., submitted manuscript, 1996] suggest that the actual meltwater flux flowing down the Mississippi River was only a fraction of that required to explain the sea- level rise during mwp-IA [*Teller*, 1990] (Figure 4). We are thus faced with an apparent conundrum between interpreting the marine and terrestrial records with respect to the magnitude of the freshwater fluxes that drained through the Mississippi River.

Two developments since *Emiliani's* [1976] work, however, suggest a solution to this issue. The first is the Barbados record itself (Figure 1), which now identifies both the magnitude and timing of sea level rise within the context of the Gulf of Mexico record. Although the total oxygen isotope anomaly in core EN32 PC-6 from 14,000 ^{14}C to 12,000 ^{14}C years B.P. is on the order of 3‰ (Figure 3b) [*Leventer et al.*, 1982; *Keigwin et al.*, 1991], the anomaly that occurs in direct association with mwp-IA is ~1.5‰. The important point here is that there are two isotopic excursions of similar magnitude that occur before mwp-IA when ice sheet meltwater entered the global ocean at a lower rate· one at about 13,000 ^{14}C years B.P. (1.5‰) and one starting about 13,800 ^{14}C years B.P. (2‰) [cf. *Keigwin et al.*, 1991]. The presence of these excursions at times when rates of sea level rise were low suggests that isotopic events in the Gulf of Mexico were recorded in the absence of extremely high freshwater fluxes down the Mississippi River.

The second development is based on observations of the entrainment of Mississippi River floodwaters into the Gulf Stream during the 1993 flood [*Ortner et al.*, 1995]. Mean peak discharge from the Mississippi River during August and September 1993 was ~0.025 Sv, or a similar flux as we estimate from our ice sheet reconstructions [see also *Teller*, 1990]. Off the Florida Keys and Miami, Florida, the surface salinity was depressed by ~2‰ in September, and remained depressed by 1‰ 6 weeks after the flood. Depressed salinity was observed as far north as Cape Lookout, North Carolina. *Ortner et al.* [1995] concluded that the following conditions favored entrainment of the flood waters into the Loop Current: (1) northward position of the Loop Current; (2) highly stratified shelf waters; and (3) westerly winds.

A 1‰ reduction in salinity is equivalent to about 3% freshwater. For this salinity reduction, therefore, Mississippi River waters would result in a reduction of ~1‰ in δ^{18}O values of Gulf of Mexico surface waters, if those flood waters had δ^{18}O values equivalent to Laurentide Ice Sheet meltwater (about -30‰ [*Mix*, 1987]). The 2‰ salinity reduction that occurred during the 1993 peak flood could thus translate into a 2‰ decrease in δ^{18}O values. The 1993 flood data thus demonstrate that an oceanographic

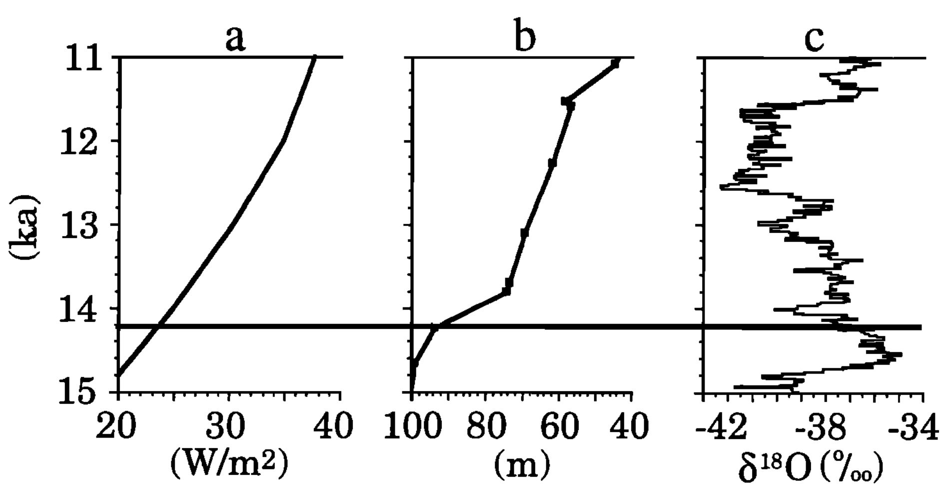

Figure 7. Comparison of (a) July insolation anomaly at 45°N between 11,000 and 15,000 years ago with (b) Barbados sea level record [from *Bard et al.*, 1990a, 1993] and (c) the GRIP oxygen isotope record (20-year means) from the Summit ice core on the Greenland Ice Sheet [from *Johnsen et al.*, 1992]. Solid horizontal line corresponds to beginning of fastest rate of sea level rise during mwp-IA (see Table 1 for corresponding ages).

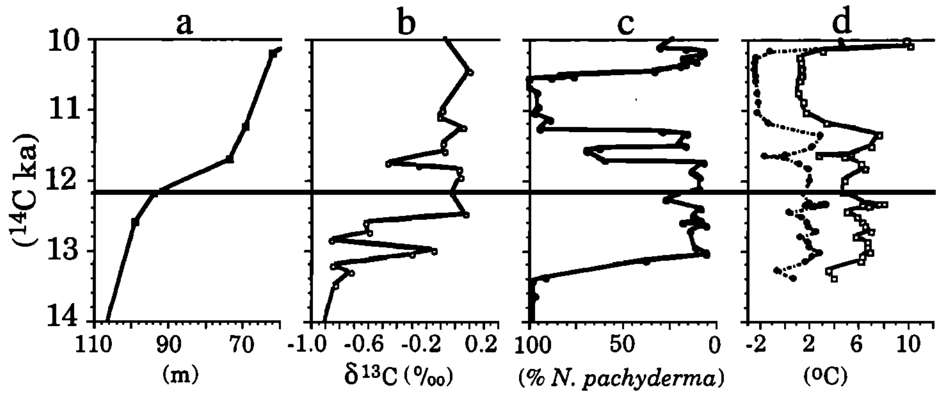

Figure 8. The Barbados sea level record compared with records that reflect changes in the strength of North Atlantic Deep Water Production between 10,000 and 14,000 ^{14}C years B.P. Solid horizontal line corresponds to beginning of fastest rate of sea level rise during mwp-IA (see Table 1 for corresponding ages). (a) Barbados sea level record dated by radiocarbon [*Fairbanks*, 1989]. (b) Carbon isotope record (core RC11-83) measured on *Planulina wuellerstorfi* from the Southern Ocean [from *Charles and Fairbanks*, 1992]. (c) Percent *N. pachyderma* (s.) (core Troll 3.1) from continental shelf of Norway [from *Lehman and Keigwin*, 1992]. (d) Reconstructed August (solid line) and February (dashed line) sea surface temperatures (core HM79-6/4) from continental slope of Norway [from *Karpuz and Jansen*, 1992].

circulation can exist which can advect a rather modest freshwater signal far seaward and result in a δ^{18}O signal such as that recorded in the Gulf of Mexico Pleistocene record.

Deglaciation, Meltwater Routing and the Oxygen Isotope Record

Here we follow *Kennett and Shackleton* [1975], *Farrand and Evenson* [1976], and *Leventer et al.* [1982] in interpreting the Gulf of Mexico oxygen isotope record as simply identifying the interplay between (1) meltwater discharge from the southern margin of the ice sheet associated with increasing insolation and (2) the routing of that meltwater along the ice sheet margin during the last deglaciation. *Kennett and Shackleton* [1975] had no direct radiocarbon age control for the Gulf of Mexico cores they examined, and the chronology of the core studied by *Emiliani et al.* [1975, 1978] was based on only few conventional bulk radiocarbon ages. The chronology of the Gulf of Mexico core examined here (EN32 PC-6) (Figure 3b) is based on several accelerator mass spectrometry (AMS) ^{14}C ages [*Broecker et al.*, 1988, 1989] which allow a more precise comparison with the history of meltwater routing along the southern ice sheet margin than discussed by *Leventer et al.* [1982]. *Broecker et al.* [1989] made a similar interpretation of the younger part of the Gulf of Mexico isotope record (<11,000 ^{14}C years B.P.) as reflecting meltwater routing along the southern ice sheet margin. *Keigwin et al.* [1991] also interpreted variations in surface water salinities in the North Atlantic as recording geographic variability in meltwater input.

We converted the radiocarbon chronology of this record to calendar years using the relation defined by *Bard et al.* [1993] to compare it with insolation anomalies for July at 45°N, a latitude which spans the southern margin of the Laurentide Ice Sheet. In general, this comparison shows that the rise in insolation is closely matched by an increase in melting along the southern margin (as suggested by the oxygen isotope record) (Figure 9)

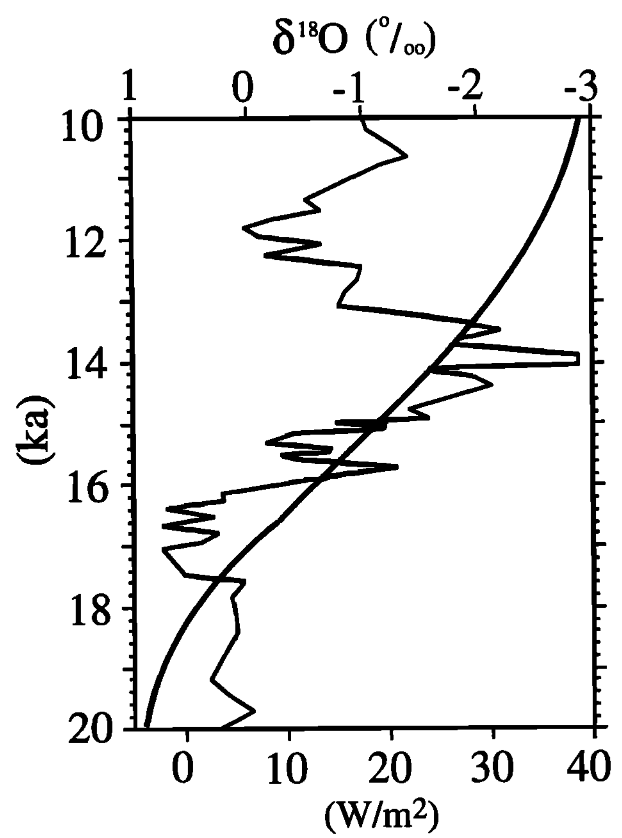

Figure 9. Oxygen isotope record from the Gulf of Mexico (core EN32 PC-6), with radiocarbon age chronology converted to calendar years using relation of *Bard et al.* [1993], compared with July insolation anomaly at 45°N between 10,000 and 20,000 years ago.

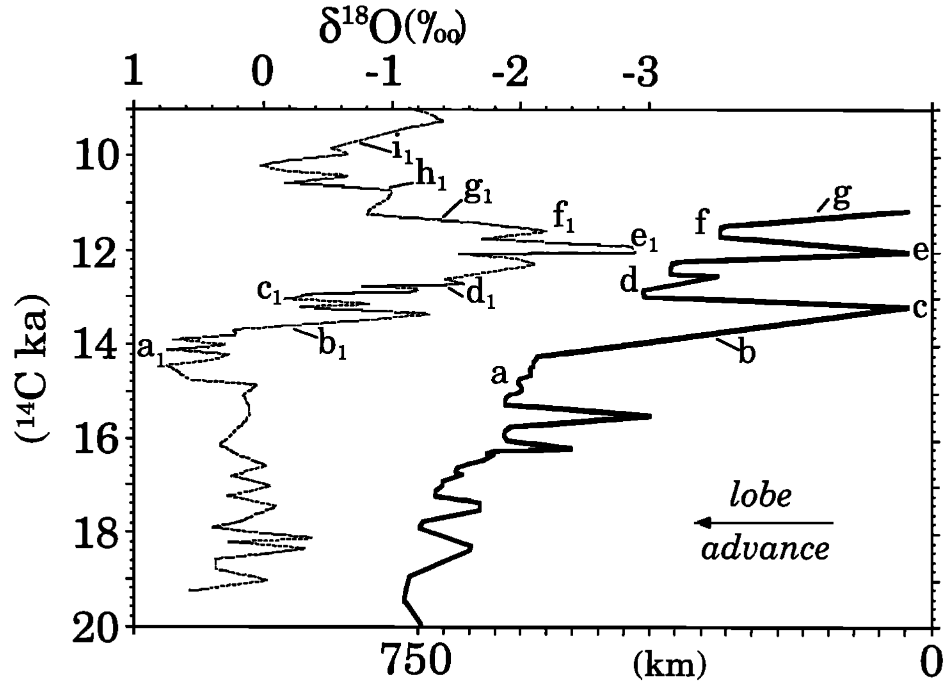

Figure 10. Oxygen isotope record from the Gulf of Mexico (core EN32 PC-6) (dased line) [from *Keigwin et al.*, 1991] compared with record of advance and retreat of the Lake Michigan Lobe of the Laurentide Ice Sheet [from *Hansel and Johnson*, 1992] between 9,000 and 20,000 ^{14}C years B.P. Lowercase labels (a - g, a_1 - i_1) are discussed in text.

until about 14,000 years ago (12,000 ^{14}C years B.P.), when $\delta^{18}O$ values suddenly become more positive. If meltwater routing is also important in explaining the Gulf of Mexico record [*Kennett and Shackleton*, 1975; *Farrand and Evenson*, 1976; *Leventer et al.*, 1982; *Broecker et al.* 1989; *Keigwin et al.*, 1991], then secondary fluctuations seen in that record as well as the abrupt shift at 14,000 years should correspond closely to times when eastern outlets opened or were closed, resulting in changes in the flux of meltwater flowing through the Mississippi River.

Meltwater flowing to the Mississippi River was derived from one of several possible hydrological basins [*Teller*, 1990, 1995]. The westernmost basin, corresponding to the area eventually containing glacial Lake Agassiz, drained to the Mississippi River unless an eastern outlet opened to the Lake Superior basin [*Teller*, 1985]. The next basin to the east, corresponding to the basins of Lakes Superior and Michigan, drained to the Mississippi River unless the ice margin retreated north, thus opening eastern outlets near or through the Straits of Mackinac [*Hansel and Mickelson*, 1988]. The next basin, corresponding to the basins of Lakes Huron, Erie, and Ontario, drained to the west into the Lake Michigan basin and then into the Mississippi River unless the ice margin retreated enough to allow waters to drain eastward across New York to the Mohawk River or, with further ice margin retreat, to the St. Lawrence River [*Clark and Karrow*, 1984; *Calkin and Feenstra*, 1985].

In order to evaluate the hypothesis that fluctuations in the Gulf of Mexico oxygen isotope record reflect changes in meltwater routing, we compare this record with the record of ice-margin fluctuations reconstructed for the Lake Michigan Lobe of the Laurentide Ice Sheet (Figure 10) [*Hansel and Johnson*, 1992]. The Lake Michigan Lobe record is important because it identifies times when meltwater from some or all of the Great Lakes basins was draining to the Mississippi River instead of to eastern outlets [*Hansel and Mickelson*, 1988].

The ice margin reached its maximum extent ~19,500 ^{14}C years B.P. and then began a gradual retreat with several minor oscillations until rapid retreat at ~15,500 ^{14}C years B.P. This was followed by a significant readvance between 15,200 and 14,100 ^{14}C years B.P. (Figure 10), which is recorded elsewhere along the southern ice sheet margin (Port Bruce stadial; *Dreimanis* [1977]). This readvance (labeled a on Figure 10) may be responsible for the increase in $\delta^{18}O$ values seen in the Gulf of Mexico between ~15,000 and 13,700 ^{14}C years B.P. (labeled a_1).

Following this readvance, the ice margin began a major retreat (labeled b) during the Mackinaw interstadial [*Dreimanis and Karrow*, 1972]. Meltwater was initially directed from all basins into the Mississippi River, but by about 13,300 ^{14}C years B.P. the southern ice margin retreated far enough to the north (labeled c) to open drainage routes to the east for all meltwater in the Great Lakes basins [*Calkin and Feenstra*, 1985; *Hansel and Mickelson*, 1988; *Teller*, 1995]. This retreat history seems to be well recorded in the Gulf of Mexico, where $\delta^{18}O$ values initially decreased (labeled b_1), reflecting ice sheet melting, and then abruptly increased (labeled c_1) at the same time as the opening of eastern outlets in the Great Lakes region.

The southern ice margin in much of the Great Lakes region then began to readvance several hundred kilometers during the Port Huron stadial, reaching its maximum position by about 13,000 ^{14}C years B.P. (labeled d) [*Dreimanis and Karrow*, 1972; *Dreimanis*, 1977]. This readvance closed all eastern outlets again, forcing drainage back to the Mississippi River [*Calkin and Feenstra*, 1985; *Eschman and Karrow*, 1985; *Hansel and Mickel-*

son, 1988]. This rerouting of meltwater is recorded by decreasing $\delta^{18}O$ values in the Gulf of Mexico (labeled d_1). Meltwater in the Huron, Erie, and Ontario basins continued to drain west to the Michigan basin until about 12,400 ^{14}C years B.P., when ice retreat again began to uncover eastern outlets [*Calkin and Feenstra*, 1985]. Meltwater in the Lake Michigan basin, however, continued to drain to the Mississippi River, probably at an increasing rate as the margin was retreating and July insolation was within 80% of its maximum level (Figure 9). Thus $\delta^{18}O$ values continued to decrease despite the loss of meltwater from the eastern Great Lakes basins.

About 12,000 ^{14}C years B.P., or the beginning of the Two Creeks interstade [*Kaiser*, 1994], retreat of the ice margin (labeled e) uncovered an outlet just to the south of the Straits of Mackinac, allowing meltwater in the Lake Michigan basin to drain to the east [*Hansel and Mickelson*, 1988]. This diversion is contemporaneous with and thus may explain the abrupt increase in $\delta^{18}O$ values in the Gulf of Mexico following the point labeled e_1 (Figure 10). The last ice readvance recorded in the Lake Michigan basin (labeled f) began after 11,750 ^{14}C years B.P. [*Kaiser*, 1994], forcing meltwater in this basin to again drain briefly to the Mississippi River, possibly as late as 11,100 ^{14}C years B.P. [*Hansel and Mickelson*, 1988]. This may explain the brief decrease in $\delta^{18}O$ values at the same time (labeled f_1). Subsequent retreat of the ice margin (labeled g) resulted in all meltwater from the Great Lakes basins to drain to the east, resulting in increasing $\delta^{18}O$ values (labeled g_1). *Broecker et al.* [1989] attributed the next significant increase in Gulf of Mexico $\delta^{18}O$ values (starting at point h_1) to diversion of glacial Lake Agassiz waters from the Mississippi River to the St. Lawrence River, followed by renewed drainage to the Mississippi River and decreasing $\delta^{18}O$ values (labeled i_1) when ice readvanced into the Lake Superior basin at about 10,000 ^{14}C years B.P.

Discussion

Oceanic and terrestrial records show no evidence for accelerated deglaciation of any of the northern hemisphere ice sheets at the time of mwp-IA. Our evaluation of the history of deglaciation of global ice sheets during mwp-IA is based on the assumption that this event represents the rapid collapse of some portion of an ice sheet, resulting in the deglaciation of the equivalent of two to three Greenland Ice Sheets in <500 years. We thus assume that the rapid rate of sea level rise during mwp-IA records either accelerated ice sheet melting in response to an abrupt warming event or collapse of a marine-based portion of an ice sheet by calving.

Because the North Atlantic and Arctic Oceans received all meltwater and icebergs from the former northern hemisphere ice sheets, records from these oceans should identify rapid ice sheet collapse at the time of mwp-IA as an excursion to lighter $\delta^{18}O$ values and/or increased IRD fluxes. In all of the records of deglaciation of the northern hemisphere ice sheets that we reviewed, only those from the Gulf of Mexico, the Blake Outer Ridge, and the Bermuda Rise recording meltwater drainage from the southern Laurentide Ice Sheet down the Mississippi River show any indication of a significant excursion to lighter $\delta^{18}O$ values at the time of mwp-IA (Figure 3). However, the southern Laurentide Ice Sheet seems an unlikely source of mwp-IA for several reasons. First, on the basis of our understanding of ice volume contained within the sector of the Laurentide that drained to the Mississippi River, the likely flux of meltwater during the time of mwp-IA was only a fraction (<10%) of that needed to raise sea level at the rate suggested by mwp-IA. Geological records from the area of the southern Laurentide Ice Sheet indicate only slight withdrawal of the ice margin [*Dyke and Prest*, 1987], unlike the amount required if this ice sheet sector were responsible. Even if enough ice were present within that sector of the ice sheet, melting it at the necessary rate is physically implausible. In addition, such an accelerated melting rate required for the Mississippi ice sheet sector raises the question of why only that sector would be so sensitive to ablation, whereas adjacent sectors were relatively insensitive, as suggested by the absence of significant meltwater drainage in records from the Gulf of St. Lawrence [*Keigwin and Jones*, 1995] and Hudson Strait [*Andrews et al.*, 1994; *Hillaire-Marcel et al.*, 1994] (Figure 3). Furthermore, ocean modeling results (Figure 6) predict a much stronger climatic response to a large freshwater flux out of the Mississippi River than is recorded in the North Atlantic region (Figures 7 and 8). Finally, there is no obvious forcing mechanism that would result in such a brief but intense period of ablation of the Mississippi ice sheet sector. Insolation during this time increased gradually (Figure 9), and warming associated with intensified formation of NADW in the Norwegian and Greenland Seas is expected to strongly affect only the Eurasian ice sheets [*Rind et al.*, 1986; *Manabe and Stouffer*, 1988], although there is no evidence for accelerated melting of the Eurasian ice sheets at the time of mwp-IA (Figure 5).

The only other ice sheet capable of delivering enough volume to explain the sea level rise that defines mwp-IA therefore is the Antarctic Ice Sheet. However, there are currently no high-resolution records of deglaciation of the Antarctic Ice Sheet to evaluate whether it was responsible for mwp-IA. Moreover, the amount of extra ice contained in this ice sheet at the last glacial maximum, as well as the timing of its release to the ocean during the last deglaciation, remains uncertain. Estimates of the contribution to sea level lowering by the Antarctic Ice Sheet during the last glacial maximum range from as little as 0.5 m [*Colhoun et al.*, 1992] to 37 m [*Nakada and Lambeck*, 1988]. The small ice-volume estimates made by *Colhoun et al.* [1992] are based on Holocene raised beaches found at relatively low altitudes. They calculated an ice thickness based on the assumption that the height of Holocene beaches is a function only of former ice thickness. Because the height of a raised beach is also a function of the rate of ice thinning prior to deglaciation [*Andrews*, 1970], however, their estimates of ice thickness are only minima; a substantial amount of uplift may have occurred beneath the thinning ice load during deglaciation before the site became ice free, and the maximum ice load may have been significantly greater.

Much of the geological and geophysical evidence appears to support 15-20 m of additional sea level within the Antarctic Ice Sheet at the last glacial maximum. *Hughes et al.* [1981] suggested that the Antarctic Ice Sheet may have contained as much as 24 m of additional sea level during the last glacial maximum, with ~16 m present within an expanded West Antarctic Ice Sheet, although this latter estimate is likely too high [*Denton et al.*, 1989]. *Huybrechts* [1990a, b] modeled an additional 12-16 m sea level equivalent in a full-glacial Antarctic Ice Sheet. *Tushingham* *and Peltier* [1991] constrained 26 m of additional sea level, and *Peltier* [1994] constrained 21.8 m. We note that if the Antarctic Ice Sheet contained ~22 m of additional sea level [*Peltier*, 1994], of which ~19 m was released during mwp-IA, then only 3 m of additional ice would remain from ~12,000 ^{14}C years B.P. until sites described by *Colhoun et al.* [1992] became ice free <7,500 ^{14}C years B.P. This would allow a significant amount of uplift to occur beneath the dynamically thinned ice cover before their sites became ice free.

Because much of the extra ice in both the East Antarctic and West Antarctic Ice Sheets was grounded below sea level during the last glaciation, these ice sheets would have been susceptible to rapid collapse as sea level rose following the last glacial maximum [*Hollin*, 1962; *Stuiver et al.*, 1981; *Denton and Hughes*, 1983]. The timing of deglaciation remains poorly constrained, however, although many existing data can be interpreted as consistent with, and perhaps providing preliminary evidence for, our hypothesis that the source of mwp-IA was from the Antarctic Ice Sheet. *Denton et al.* [1989] dated initial deglaciation of the Ross Sea ice drainage system of the Antarctic Ice Sheet as beginning as late as 12,500-13,000 ^{14}C years B.P., while *Licht et al.* [1996] dated deglaciation in the Ross Sea area as beginning by at least 11,500 ^{14}C years B.P.

In deep-sea cores from the Indian sector of the Southern Ocean, *Labeyrie et al.* [1986] found isotopic anomalies interpreted as meltwater events occurring between 17,000 and 35,000 years ago. In the same cores, but now with AMS ^{14}C age control, *Labracherie et al.* [1989] and *Bard et al.* [1990b] found that sea surface temperatures were nearly the same as modern values by 13,000 ^{14}C years B.P., but were then replaced by a cool period between 12,000 and 11,000 ^{14}C years B.P., or roughly contemporaneous with mwp-IA More important to our hypothesis, *Labracherie et al.* [1989] and *Bard et al.* [1990b] identified a significant light peak in δ^{18}O values from one core, having an age centered at 11,920 $\pm$ 200 ^{14}C years B.P. (800-year reservoir age correction). Because this peak does not coincide with a change in SST, *Bard et al.* [1990b, p. 413] concluded that this isotopic event could be "a response to a pulse-like injection of [a] large volume of ice or meltwater."

Shemesh et al. [1995] examined δ^{18}O records of biogenic silica from the Atlantic sector of the Southern Ocean. Their cores lacked radiocarbon age control, although the level of the last glacial maximum is identified from biostratigraphy. *Shemesh et al.* [1995] identified a post-glacial-maximum spike-shaped decrease in δ^{18}O values in cores associated with the Weddell gyre. The amplitude of this "meltwater" spike decreases in a northeastern direction, suggesting increasing dilution with distance from Antarctica toward the South Atlantic. On the basis of preliminary age models for these cores, *Shemesh et al.* [1995] concluded that the meltwater spike occurred sometime between 15,000 to 10,000 ^{14}C years B.P. and that it may be correlative with mwp-IA.

Finally, using the δ^{18}O of atmospheric O_2 trapped in ice cores, *Sowers and Bender* [1995] placed the chronology of the Byrd ice core, West Antarctica [*Johnsen et al.*, 1972], on the same timescale as the Greenland Ice Sheet Project (GISP2) ice core from Greenland. A small decrease in δ^{18}O values (~2‰) observed in the Byrd ice core during the last deglaciation, also seen as an oscillation in deuterium profiles in ice cores from East Antarctica and referred to as the Antarctic cold reversal [*Jouzel et al.*, 1995], began 14,000-14,200 years ago, or immediately after initiation of mwp-IA (Figure 11). If this event is associated with mwp-IA, it may indicate cooling of the Antarctic continent as a result of increased ice cover over the surrounding ocean following ice sheet collapse. Alternatively, it may represent an increase in isotopic fractionation during moisture transport to the ice sheet as the source waters were displaced northward by increased ice cover over the surrounding ocean.

Peltier [1988] and *Tushingham and Peltier* [1991] argued that deglaciation of the Antarctic Ice Sheet began well after initial deglaciation of the northern hemisphere ice sheets, and *Peltier* [1994] constrained the Antarctic Ice Sheet as the source of the second meltwater pulse (mwp-IB) (Figure 1). Geological records of Antarctic deglaciation reviewed above, however, may be more consistent with an earlier deglaciation, similar in timing to mwp-IA, although better resolution is clearly required to support this hypothesis. Nevertheless, the sensitivity of the Earth models described by *Peltier* [1988, 1994] to changes in timing of Antarctic Ice Sheet deglaciation and other model parameters (e.g., lithosphere thickness, mantle viscosity) [cf. *Davis and Mitrovica*, 1996] and assumptions of isostatic equilibrium [cf. *Mitrovica and Davis*, 1995] in explaining far-field sea level records suggest that an evaluation of the Antarctic Ice Sheet as the source of mwp-IA may be warranted.

Our conclusion that the former northern hemisphere ice sheets were not responsible for mwp-IA has two important implications. First, because *Peltier* [1994] constrained the Laurentide Ice Sheet to be the source of mwp-IA in his ICE-4G model, we suggest that his reconstructions of the Laurentide Ice Sheet surface elevations during the last deglaciation may be too low for time periods younger than 15,000 years ago.

Second, our interpretation that the δ^{18}O record of meltwater discharge from the Mississippi River to the Gulf of Mexico identifies the interplay between insolation forcing of melting rates and the routing history of meltwater along the southern ice sheet

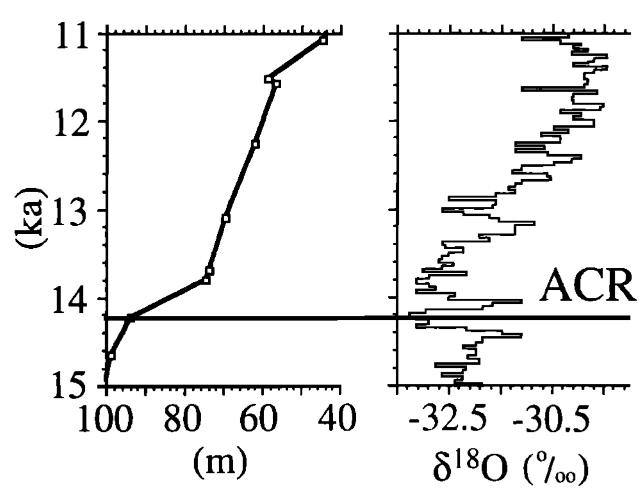

Figure 11. The Barbados sea level record [*Bard et al.*, 1990a, 1993] compared with the Byrd ice core δ^{18}O record (δ^{18}O values from *Johnsen et al.* [1972]; age model of ice core from *Sowers and Bender* [1995]). Solid horizontal line corresponds to beginning of fastest rate of sea level rise during mwp-IA (see Table 1 for corresponding ages). ACR denotes Antarctic cold reversal [*Jouzel et al.*, 1995].

margin has important implications regarding the sensitivity of NADW formation to freshwater injections. *Haskell et al.* [1991] and *Keigwin et al.* [1991] identified four periods of reduced flow of NADW during the last deglaciation (14,500 to 10,000 ^{14}C years B.P.) superimposed on a general trend of increasing flow, and *Keigwin et al.* [1991] associated each period with a period of freshwater injection into the North Atlantic. The earliest period corresponds to the low $\delta^{18}O$ values recorded in the Nordic seas (Figure 5) and Heinrich event 1 [*Keigwin and Lehman*, 1994], whereas the most recent period corresponds to the Younger Dryas, which may have its origin in the diversion of drainage of glacial Lake Agassiz from the Mississippi River to the St. Lawrence River [*Broecker et al.*, 1989] and the release of icebergs to the North Atlantic during Heinrich event 0 [*Miller and Kaufman*, 1990; *Andrews et al.*, 1995].

We interpret the cause of the two intervening periods of reduced NADW formation to diversion of meltwater drainage along the southern Laurentide Ice Sheet margin to eastern outlets, unlike *Keigwin et al.* [1991], who interpreted them as resulting from periods of increased discharge through the Mississippi River. These two periods of reduced NADW formation just postdate prominent peaks seen in the oxygen isotope records from the Gulf of Mexico (the first peak occurring between b_1 and c_1 and the second peak, labeled f_1 on Figure 10, equivalent to events b and c, respectively, given by *Keigwin et al.* [1991]), Bermuda Rise (Figure 3b), and Blake Outer Ridge [*Haskell et al.*, 1991; *Keigwin et al.* 1991]. As was discussed, the expression of these $\delta^{18}O$ peaks represents meltwater diversion from the Mississippi River to eastern outlets. The first diversion occurred during the Mackinaw interstadial such that by ~13,300 ^{14}C years B.P., all meltwater drained to the east and into the North Atlantic through the Hudson River. At the same time, there was a significant increase in the discharge of icebergs through the Gulf of St. Lawrence [*Bond and Lotti*, 1995; *Keigwin and Jones*, 1995], which would have augmented the freshwater flux to the North Atlantic. Proxy records indicate reduced formation of NADW during this time [*Haskell et al.*, 1991; *Keigwin et al.*, 1991]. Following 13,000 ^{14}C years B.P., however, the southern margin of the Laurentide Ice Sheet readvanced and diverted meltwater back to the Mississippi River, iceberg discharge from the Gulf of St. Lawrence decreased, and the rate of formation of NADW increased.

The next younger period of reduced NADW formation was brief, occurring ~12,000-12,200 ^{14}C years B.P. The timing of this event seems to correspond closely to renewed meltwater discharge to the east, culminating with the Two Creeks interstade when meltwater from the Michigan, Huron, Erie, and Ontario basins was draining to the North Atlantic initially through the Hudson River and then through the St. Lawrence River. The effect of this easterly drainage on the observed reduction of NADW formation, if indeed involved, was short-lived, perhaps as a result of the stronger mode of formation of NADW at the time, compared with earlier events, as suggested by Cd/Ca data [*Keigwin et al.*, 1991].

This discussion reiterates arguments by *Broecker et al.* [1989] and *Keigwin et al.* [1991] that discharge of icebergs and rerouting of meltwater along the southern margin of the Laurentide Ice Sheet may have been important in affecting NADW formation. In the above scenario, however, only significant freshwater discharge to the North Atlantic from routes north of the Mississippi (i.e., Hudson River, St. Lawrence River, and Hudson Strait) seem to have affected NADW formation. These discharge events may in turn have been controlled by surging behavior of the Laurentide Ice Sheet, both in terms of controlling the flux of icebergs [*MacAyeal*, 1993] and the routing of meltwater along the ice sheet margin [*Clark*, 1994], thus reinforcing an ice sheet forcing mechanism that resulted in high-frequency climate change.

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R. B. Alley, Earth System Science Center and Department of Geosciences, Pennsylvania State University, University Park, PA 16802. (e-mail: ralley@essc.psu.edu)

P. U. Clark and J. M. Licciardi, Department of Geosciences, Oregon State University, Corvallis, OR 97331. (e-mail: clarkp@ucs.orst.edu; licciarj@bcc.orst.edu)

S. J. Johnsen, Niehls Bohr Institute, Department of Geophysics, University of Copenhagen, Haraldsgade 6, 2200 Copenhagen N., Denmark. (e-mail: sigfus@osiris.gfy.ku.dk)

L. D. Keigwin, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. (e-mail: lkeigwin@cliff.whoi.edu)

H. Wang, Atmospheric Science Division, Lawrence Livermore National Laboratory, P.O. Box 808, L-256, Livermore, CA 94550. (e-mail: huaxiao@extreme.llnl.gov)

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