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Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation

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Abstract

Lake Agassiz was the largest lake in North America during the last deglaciation. As the Laurentide Ice Sheet (LIS) retreated, large volumes of water stored in this proglacial lake were episodically released into the oceans. These waters were variably routed to the Gulf of Mexico, Arctic Ocean, North Atlantic Ocean, and Hudson Bay. During this period, the three largest cooling events in the Northern Hemisphere closely followed 4 of the 5 largest outbursts from Lake Agassiz: (1) the Younger Dryas, which was preceded by a release of 9500 km^3, (2) the Preboreal Oscillation, preceded by releases of 9300 km^3 and 5900 km^3, and (3) the "8.2 ka cold event", preceded by a 163,000 km^3 outburst; these are, respectively, fluxes of 0.30 Sv, 0.29 Sv, 0.19 Sv, and 5.2 Sv if released in 1 year. Because the influx of freshwater reaching the North Atlantic Ocean can inhibit thermohaline circulation, partly depending on whether the ocean was in a glacial, interglacial, or transitional mode of circulation, we believe that at least these large outbursts from Lake Agassiz may have provided the triggers for changes in ocean circulation and, in turn, for widespread climate change.

1. Introduction

During melting of the Laurentide Ice Sheet (LIS), many thousands of years of stored precipitation were returned to the oceans. Proglacial Lake Agassiz was the largest lake in North America and contained the largest volume of freshwater. As the southern margin of the LIS retreated downslope, lower outlets from Lake Agassiz were periodically available, resulting both in the sudden release of thousands of cubic kilometers of water and, at times, in a change in the routing of runoff to the oceans. A *change in the routing* of freshwaters from North America to the North Atlantic Ocean has been linked with past changes in ocean circulation and climate (e.g. Johnson and McClure, 1976; Broecker et al., 1988; Keigwin et al., 1991; Licciardi et al., 1999; Clark et al., 2001), and several have suggested that an initial outburst of freshwater may also have contributed to this change (e.g. Björck et al., 1996; Alley, 2000; Leverington et al., 2000; Alley et al., 2001; Clark et al., 2001). The potential impact of short *outbursts* from Lake Agassiz by themselves, however, has only been discussed in regard to the final draw down of the lake (Barber et al., 1999); Clark et al. (2001) suggest that a "two-stage sequence of freshwater forcing" from Lake Agassiz may have been involved in suppressing the formation of North Atlantic Deep Water (NADW). Expanding on the idea that outbursts may have played a significant role in altering ocean circulation, this paper quantifies the fluxes of large outbursts that occurred when new outlets were opened from Lake Agassiz, using the bathymetric models of Leverington et al. (in press). In order to evaluate the role that specific outburst fluxes alone may have played in altering late glacial thermohaline circulation (THC), our discussion focuses on the relationship of the magnitude of various Lake Agassiz outbursts to specific known changes in climate and to the freshwater flux that various models have shown may impact on THC.

Some models have shown that a freshwater influx of <0.1 Sv (1 sverdrup $= 1 \times 10^6$ m^{3}s^{-1}) may slow or shut down the production of NADW and, in turn, alter global ocean circulation patterns and related climate (e.g. Rahmstorf, 1994, 1995a; Fanning and Weaver, 1997; Manabe and Stouffer, 1997; Rind et al., 2001). Although some of this freshwater would have entered

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the oceans directly from the ice margin when it lay near the coast, both as meltwater and as icebergs, most North American runoff was delivered by way of five main runoff routes (Teller, 1995; Licciardi et al., 1999). Using numerical reconstructions for the LIS and results from a model of glacial-age precipitation, Licciardi et al. (1999) found that the cumulative *total* ''baseline'' flux of meltwater and precipitation runoff entering the oceans from glaciated North America through all five of these routes remained nearly constant at about 0.3 Sv between 18 and 8.5 ka radiocarbon years ago (ca 21.4–9.5 ka calendar years); this constant ''baseline'' flow resulted from complementary changes in melting and precipitation. Marshall and Clarke (1999) used coupled ice-sheet dynamics and surface hydrology modeling to calculate runoff, and the results again showed that the cumulative total runoff during the last deglaciation remained nearly constant, ranging mainly from 0.3 to 0.4 Sv. However, as a result of the fluctuating ice margin and its impact on the routing of continental runoff, it is known that the flux of freshwater reaching the oceans through each individual runoff route was highly variable. Thus, the impact of North American runoff on thermohaline circulation, production of NADW, ocean heat transport, and, in turn, on hemispheric temperature would have varied through time because of the different sites into which these freshwaters were directed, in spite of the relatively constant total volume of runoff (Clark et al., 2001).

In addition to the ''baseline'' flow from the melting LIS, waters were temporarily stored in proglacial lakes and then periodically released. There were a number of lakes along the LIS margin whose confining ice or sediment dams failed during deglaciation, but glacial Lake Agassiz was by far the largest (Teller, 1987). Covering a total of more than a million km^2 over its 4000-year history (Fig. 1), and commonly more than 150,000 km^2 at any point in time, this lake frequently changed configuration, depth, and volume because of the interplay between ice margin position, subglacial topography, isostatic rebound, and outlet erosion (Teller, 1987, 1995, 2001). The extent of the lake at various times is outlined by the many strandlines (beaches and wave-cut cliffs) that formed around its margin; as water levels changed, new strandlines were constructed. Usually these changes were abrupt and, on many occasions, several thousand cubic kilometers were released into newly opened overflow channels, even-

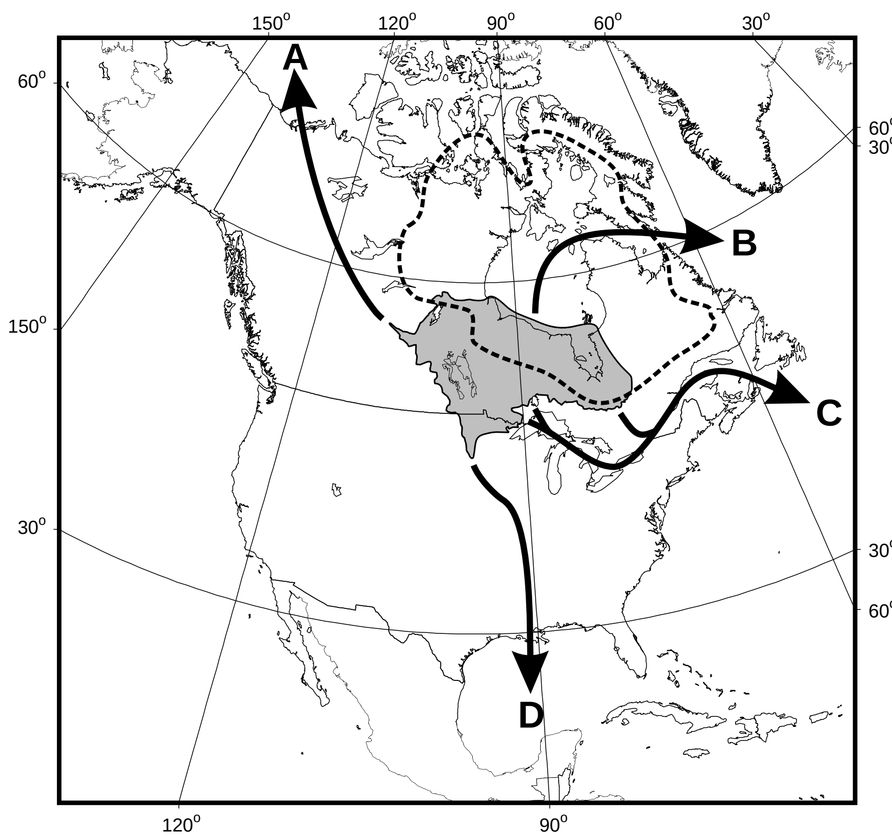

Fig. 1. Map showing general routing of Lake Agassiz overflow and outbursts to the oceans. Total area covered by Lakes Agassiz and Ojibway is shaded (modified from Teller et al., 1983; Dredge and Cowen, 1989). General outline of the Laurentide Ice Sheet at 9 ka ^{14}C years BP is shown by dashed line (after Dyke and Prest, 1987). Runoff routes are identified as: A = Mackenzie Valley to Arctic Ocean, B = Hudson Bay to North Atlantic Ocean, C = St. Lawrence to North Atlantic Ocean, and D = Mississippi Valley to Gulf of Mexico.

tually flowing to the ocean through one of four routes that carried water from Lake Agassiz (Fig. 1): Mississippi River Valley, St. Lawrence Valley, Mackenzie River Valley, and Hudson Strait. Each time a new outlet became available, there was a rapid release of water and the level of the lake was drawn down; following this outburst, baseline outflow from the lake was resumed along a new route to the ocean.

Leverington et al. (in press) calculated the volume of water in proglacial Lake Agassiz at 13 different stages, based on well-defined strandlines that outline the lake basin and on the bathymetry of the lake basin determined from elevations of the Global Land One-Kilometer Base Elevation (GLOBE) database (GLOBE Task Team, 1999). The paleo-water planes and paleo-bathymetric surfaces of the isostatically deformed Lake Agassiz basin were interpolated, using isostatic rebound curves established by others (Johnston, 1946; Teller and Thorleifson, 1983; Thorleifson, 1996; Leverington et al., 2000). The complete outline of each lake phase was defined implicitly by the interpreted rebound surfaces, which themselves are based on selected well-defined strandline elevations. Ice-bounding margins of Lake Agassiz and the locations and elevations of its outlets were derived from several sources (e.g. Dredge, 1983; Klassen, 1983; Teller and Thorleifson, 1983; Dyke and Prest, 1987; Fisher and Smith, 1994), as were the glacial boundaries of coeval Lake Ojibway, which lay to the east of Lake Agassiz and merged with Agassiz in the latter stages of its history (Vincent and Hardy, 1979; Veillette, 1994). At any given time, overflow from the lake occurred through a single outlet, although the specific outlet used varied through time. As described by Teller (2001), all of the strandline-forming levels were separated by low-water phases of the lake; therefore, we established the level of water in the intervening low-water phase using the appropriate outlet channel depth in order to estimate the volume of water released during the shift from one phase to ano-ther (Leverington et al., 2000, accepted for publication).

2. Volumes, fluxes, and routings of Lake Agassiz outbursts

The volumes of water released from Lake Agassiz at 10 different times, ending each of the 10 associated lake stages, are shown in Table 1, as are the times of the outbursts and the general routes to the ocean through which these bursts flowed. The exact length of time for each lake stage to be drawn down (the outburst) can only be estimated, mainly because the original geometries of the overflow channels and the depths of flow in them can only be estimated. Given the likely paleogeometry and depth of flow, we believe that lake levels for most if not all of the phases measured could have been drawn down in months to only a few years, in all cases probably in less than a decade. This short length of time for the draw down is supported by other estimates of flow through various Agassiz outlet routes (Teller and Thorleifson, 1983; Teller, 1990a; Fisher and Smith, 1994; Barber et al., 1999).

The Flood Flux in Table 1 is the rate of freshwater flow to the oceans due to a given lake drawdown (outburst) if it occurred over a period of 1 year. The Agassiz Baseline flux is the continuing and relatively constant flow of runoff through the Lake Agassiz outlet used by the outburst. Fig. 2 plots the flux of these outbursts against time, and shows a range of possible fluxes for alternative scenarios for the ice margin as compared to the "preferred" (most likely) ice margin reconstruction; the total baseline flows through three of the main routes to the oceans, which includes any Agassiz Baseline flow, are also plotted.

The largest outburst occurred when ice over Hudson Bay collapsed about 7.7 ka radiocarbon years ago (ca. 8.4 ka calendar yrs) (Barber et al., 1999). By this time Lake Agassiz had merged with glacial Lake Ojibway, which lay along the LIS margin in the southeastern part of the Hudson Bay basin, forming a lake with a surface area of about 841,000 km^2 (Leverington et al., in press); this is more than twice the size of the largest lake in the modern world, the Caspian Sea, and larger than modern-day Hudson Bay (Hendendorf, 1984). When outflow into a partly ice-free Hudson Bay basin began, waters of this lake were rapidly drawn down. If all of this lake was drawn down from its maximum depth at the Kinojévis level, about 163,000 km^3 of freshwater would have been abruptly released to the North Atlantic Ocean (J in Table 1). This compares to a value of 200,000 km^3 used by Barber et al. (1999), who based their number on what Veillette (1994, p. 969) called a "crude estimate". Because this outburst occurred through a breach in the LIS, and was not constrained by narrow bedrock channels as had previous outbursts, it seems likely that draw down of this freshwater mass would have occurred very rapidly. The flux would have been 5.2 Sv if this outburst occurred in 1 year (Fig. 2).

An alternative scenario for the final draw down of this lake is possible if Klassen's (1983) identification of a beach below the Kinojévis level in the western (Agassiz) portion of the basin is correct. Klassen (1983) named this the Fidler beach, and it is present only locally in the Agassiz part of the basin and, apparently, not at all in the Ojibway part. In order to explain the presence of this beach, not all of Lake Agassiz would have drained at the time the eastern (Ojibway) part of the basin did. Residual Laurentide ice must have remained southwest of James Bay in order to prevent complete drainage of the Agassiz portion of the lake into the Tyrrell Sea (Thorleifson, 1996); Leverington et al. (in press) suggest

Table 1
Volumes, fluxes, routings, and timings of 10 different Lake Agassiz outbursts

Lake stage[a]	Lake vol (km^3)[b]	Lake drop (m)[b]	Outburst vol (km^3)[b]	Flood flux (Sv)[c]	Agassiz baseline (Sv)[d]	Route of burst (previous)[e]	Time of burst in ka (^{14}C/~cal yr)
A. Herman	10,900	110	9500	0.30	0.047	East (S)	10.9/12.9
B. Norcross	13,300	52	9300	0.29	0.047	South, then Northwest (E)	10.1/11.7
C. Tintah	18,555	30	5900	0.19	0.034	South, then Northwest (NW)	9.9/11.2
D. Upper Campbell	22,700	30	7000	0.22	0.034	East[f] (NW)	9.4/10.6
E. Lower Campbell	19,100	16	3700	0.12	0.034	East[f] (E)	9.3/10.4
F. McCauleyville	16,400	10	2100	0.07	0.034	East (E)	9.2/10.3
G. Hillsboro	19,200	7	1600	0.05	0.050	East (E)	8.9/10.0
H. Burnside	10,300	12	2300	0.07	0.050	East (E)	8.5/9.5
I. The Pas	4,600	12	1600	0.05	0.035	East (E)	8.2/9.2
J. Kinojévis[g]	163,000	770	163,000	5.2	0.172	North (E)	7.7/8.4
Alternative scenario for the final draw down							
K. Kinojévis[g,h]	163,000	770 and 103	113,100	3.6		North (E)	7.7/8.4
L. Fidler	49,900	420	49,900	1.6		North (N)	7.7/8.4

[a] Defined by relict beaches that outline the paleolake.
[b] Based on data in Leverington et al. (2000, accepted).
[c] Due only to lake draw down if entirely released in one year; if >1 year, divide flux by number of years.
[d] Due to baseline runoff through Lake Agassiz outburst outlet (Licciardi et al., 1999, and unpublished data); does *not* include runoff from basins downstream from Agassiz.
[e] Previous routings (in parentheses) abbreviated: S = south to Gulf of Mexico; E = east to North Atlantic Ocean; NW = northwest to Arctic Ocean; N = north to Hudson Bay.
[f] Preceded by a brief outflow to the south (Teller, 2001).
[g] Combined Lakes Ojibway (Kinojévis stage) and Agassiz (ca. Ponton stage).
[h] There was a limited draw down of the Lake Agassiz portion of the lake at this time; the first number for the "lake drop" relates to the eastern (Ojibway) part of the basin, the second to the western (Agassiz) part.

that this ice would have been related to the Cochrane II glacial advance. In this alternative scenario, there would have been an initial outburst of about 113,100 km^3 of water when all of the eastern (Ojibway) region drained and only part of the western (Agassiz) region did; this is a flux of 3.6 Sv if draw down occurred in 1 year (K in Table 1). Once the water level of this lake had fallen below the LIS barrier southwest of James Bay, the Fidler beach formed (Thorleifson, 1996; cf. Leverington et al., in press). The subsequent failure of the restricting LIS barrier allowed the area west of the barrier (the Agassiz part) to rapidly drain the remainder of its waters, which would have provided a second large outburst of 49,900 km^3 a short time later, which is 1.6 Sv if this occurred in 1 year (L in Table 1).

The largest outbursts prior to the final demise of Lake Agassiz occurred in the earlier stages, with about 0.3 Sv added to the baseline outflow calculated by Licciardi et al. (1999) at 10.9 ^{14}C ka (12.9 ka cal yrs) and again at about 10.1 ka ^{14}C yrs (11.7 ka cal yrs). The first of these outbursts (A in Table 1) was east into the Great Lakes-St. Lawrence to the North Atlantic Ocean. The next outburst (B in Table 1) occurred in two steps, first south through the Mississippi River valley to the Gulf of Mexico and then, within a few years, northwest into the Arctic Ocean (Teller, 2001); for this reason, the outburst spanned several years, thereby reducing the actual flux to the oceans. For younger outbursts (C-I in Table 1) there would have been some erosion of each overflow channel before the lake was completely drawn down, so, again, the release of Lake Agassiz water probably spanned several years, and outflow rates may have been somewhat less than that shown as the Flood Flux in Table 1.

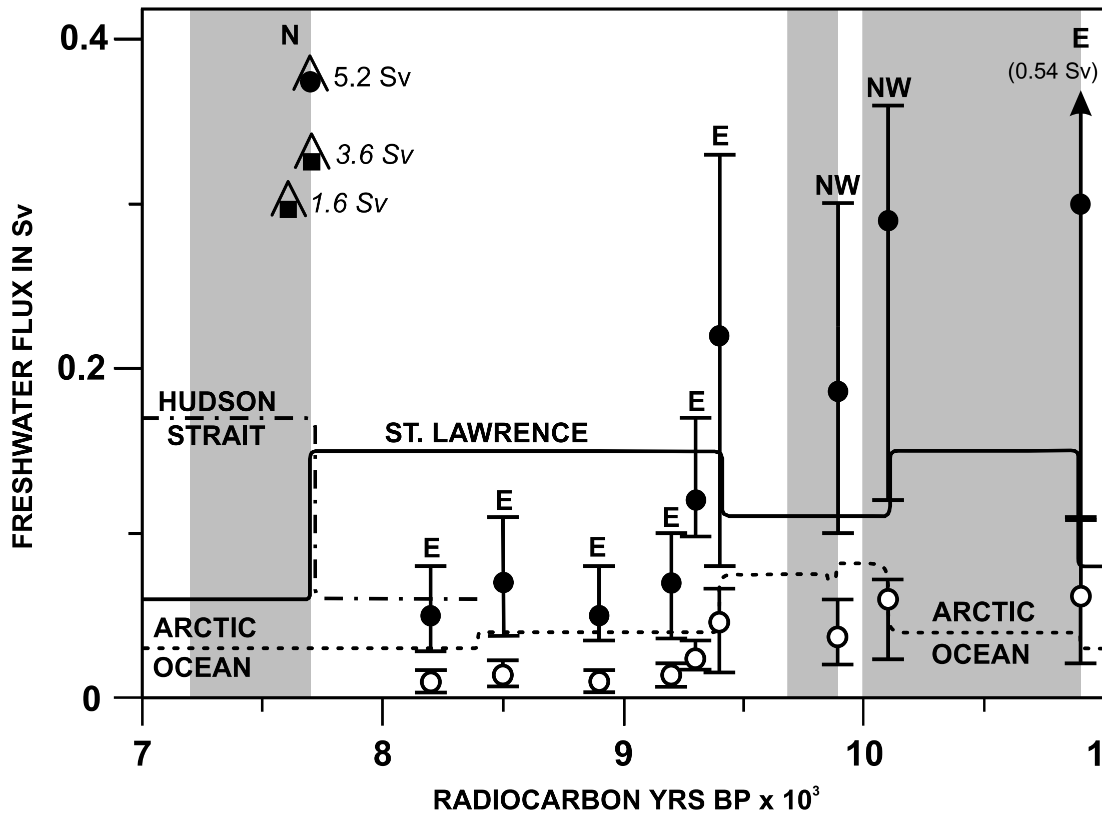

Fig. 2. Flux of 10 outbursts (in Sv) from Lake Agassiz. Solid dots show flux if lake drawdown occurred in 1 year (note that values at 7.7 and 7.6 ka exceed scale) and open circles show flux if drawdown was in five years; the two squares at 7.7–7.6 ka are alternative fluxes with a two-step draw down. The 1-year outbursts are those given in Table 1 as Flood Flux. Alternative ice margin positions would expand or reduce the volume of stored (and released) water; our range of flux resulting from a $\pm 1°$ latitude shift of the ice margin is shown by vertical lines, except at 10.9 ka where the value exceeds the scale. Baseline flows are shown as solid or broken lines and are total fluxes of outflow through each drainage basin, including Lake Agassiz baseline flow (after Licciardi et al., 1999, and unpublished data). Specific routing of outbursts designated by a letter referring to one of the routes shown in Fig. 1: NW = Mackenzie River Valley to the Arctic Ocean; E = eastern route through Great Lakes-St. Lawrence Valley to the North Atlantic Ocean; N = Hudson Bay–Hudson Strait to Labrador Sea and North Atlantic Ocean. The Younger Dryas, PBO, and the cold event at 7.7–7.2 ka ^{14}C yrs (the "8.2 ka cal yr cold event") are shaded.

3. Comparison of Lake Agassiz outbursts to models of the impact of freshwaters on ocean circulation

Because of the potential impact of freshwater runoff from large North American cryohydrological drainage basins on late-glacial ocean circulation and climate (e.g. Broecker et al., 1988, 1990; Fanning and Weaver, 1997; Barber et al., 1999; Licciardi et al., 1999; Clark et al., 2001), it is important to compare the outbursts of stored proglacial waters calculated in this paper with the impact of numerically modeled freshwater fluxes on ocean circulation. Although most of the outbursts shown in Table 1 involve relatively small volumes of water, they were added to the oceans in a very short time, possibly in critical locations and at optimal stages in the evolution of ocean circulation. Some of these outbursts alone may have been the trigger for change and, when combined with the longer-term re-direction of the Agassiz Baseline flux (Table 1), probably played an integral role in global ocean and climate history during the last deglaciation (Barber et al., 1999; Leverington et al., 2000; Clark et al., 2001). Alley et al. (2001) suggest that there has been a stochastic resonance in the North Atlantic, resulting from a combination of weak periodic forcings and irregular "noise" events such as outburst floods, each of which were too weak to cause a mode switch in THC, but together may have pushed the system over a threshold.

Numerical simulations of NADW have shown that there may be different stable modes of thermohaline circulation (THC), and that oceans are variably impacted by freshwater influxes to the North Atlantic Ocean (e.g. Manabe and Stouffer, 1988; Stocker and Wright, 1991; Weaver and Hughes, 1994; Tziperman, 1997; Ganopolski and Rahmstorf, 2001; Rind et al., 2001). According to some, small increases in freshwater flux to the North Atlantic Ocean may result in a reduction in thermohaline circulation and may even terminate production of NADW. A model by Manabe and Stouffer (1995) introduced 1 Sv of freshwater into high latitudes of the North Atlantic for 10 years, which resulted in a sudden drop in sea surface temperature

(SST) and a rapid weakening of THC. Several decades after the flux ended, there was a partial recovery of SST and THC in their model, but these again weakened and it took nearly 200 years for the system to return to previous conditions. Manabe and Stouffer (1997) indicated that as little as 0.1 Sv introduced into high North Atlantic latitudes could reduce SST by about 6° in less than a century, and dramatically reduce THC, although the rate of change is less abrupt than with larger freshwater additions. Rahmstorf (1995a) showed that a 0.06 Sv increase in fresh water flux into the North Atlantic for only a few hundred years will shut down NADW, and that convective shut down in a smaller area such as the Labrador Sea may occur with as little as a 0.015 Sv perturbation; a larger increase in the freshwater flux over a shorter period may lead to NADW shutdown. Fanning and Weaver (1997) calculated that because pre-Younger Dryas runoff to the Gulf of Mexico had reduced salinity in the North Atlantic, NADW could have been nearly shut down within 200 years by redirecting as little as 0.026 Sv of runoff through the St. Lawrence Valley, 0.004 Sv into the Davis Strait, and 0.009 Sv into the Arctic Ocean (Fanning and Weaver, 1997, Table 1, Fig. 5B). Even a 4 year "surgically injected" freshwater flux of 0.16 Sv into the North Atlantic may lead to a collapse of thermohaline circulation (Rahmstorf, 1995b).

As modeled by Rind et al. (2001), the impact on NADW production by meltwater flow through the St. Lawrence Valley is closely related to the flux, length of flow, and strength of ocean circulation. For example, a sustained freshwater flux of 0.53 Sv into a North Atlantic Ocean with normal thermohaline circulation can bring about a reduction in NADW of 10% in 6–10 years, 36% in 21–25 years, 68% in 46–50 years, and 95% in about a century; freshwater influxes of this magnitude have the capacity to cool the oceans and climate over a large area in only a century (Rind et al., 2001). A continuing flux of 0.12 Sv through the St. Lawrence reduces NADW by only 12% in 21–25 years and by 32% in a century, although if North Atlantic circulation is weaker there would be a 48% reduction within 100 years. When the freshwater input ends after complete NADW shutdown, NADW production does not resume (Rind et al., 2001).

Thus, it seems likely that the larger draw down events of Lake Agassiz (Flood Flux, Table 1)—even if the outbursts extended over a decade or more because of reduced outflow rates–would have been able to trigger a change in thermohaline circulation. When the influx occurred under weakened thermohaline conditions during the last glacial–interglacial transition, and when it was followed by an increase in baseline flow, it seems likely that THC would have been impacted by Lake Agassiz overflow on several occasions during the last deglaciation.

4. Lake Agassiz outbursts and the history of climate change

Clark et al. (2001) show the close relation between climate change and changes in routing of late-glacial baseline runoff from North America, noting the likely impact of freshwater fluxes to the North Atlantic through the St. Lawrence and Hudson River Valleys (Fig. 1). These authors discuss the oscillatory behavior of the southern margin of the LIS and present a model of the interrelationships and feedbacks of re-routing and sea surface temperature. Linkage of the Younger Dryas cold phase and the diversion of Lake Agassiz overflow away from its Mississippi River routing and into the Great Lakes-St. Lawrence about 12.8 ka cal yrs has been suggested (e.g. Broecker et al., 1989, 1990; Teller, 1990b), although it remains uncertain whether the baseline flux of re-routed freshwater into the North Atlantic Ocean was enough by itself to have initiated the Younger Dryas cold period. It is possible that preconditioning of North Atlantic THC by runoff through the Mississippi River (Fanning and Weaver, 1997; Tziperman, 1997) may have increased the sensitivity of ocean circulation to early Lake Agassiz outbursts. If the outburst from Lake Agassiz into the Great Lakes-St. Lawrence system at 10.9 ka ^{14}C yrs (12.9 ka cal yrs) occurred in 1 year, near the start of the Younger Dryas, the short flux would have been 0.30 Sv, more than 6 times the increase in Agassiz Baseline flow (0.047 Sv) through the St. Lawrence that resulted only from the addition of the Lake Agassiz drainage basin to that system at that time (Table 1). Thus, as Clark et al. (2001) suggest, it seems likely that the combination of the Lake Agassiz outburst and the diversion of one of North America's largest drainage basins into the North Atlantic Ocean during the Younger Dryas was responsible for this abrupt and dramatic cooling.

Lake Agassiz appears to have been the only source for large outbursts of stored proglacial waters in North America during deglaciation. Because Lake Agassiz did not exist much before the start of the Younger Dryas, changes in THC and climate before this could not have been triggered by its outbursts. Thus, the re-routing of the continent's drainage basins prior to the Younger Dryas, perhaps in concert with an influx of icebergs, may have been the trigger for earlier changes in THC (Clark et al., 2001).

Some of the small fluctuations in the Greenland ice-core record in the centuries following the Younger Dryas (Stuiver and Grootes, 2000), as well as in the sediment record of the Gulf of Mexico, which episodically received southerly overflow from Lake Agassiz (Teller, 2001), may reflect the frequent, but short-lived, re-directions of overflow from Lake Agassiz associated with stages B, C, D, and E (Table 1). The first notable climatic variation after the Younger Dryas was the short, cool Preboreal Oscillation (PBO), which some have attributed to reduced THC that resulted from freshwater additions to the Nordic Sea (Björck et al., 1996; Hald and Hagen, 1998). Björck et al. (1996) have summarized the evidence for the age of the PBO and conclude that it is almost impossible to assign a precise age, although it probably began about 2–3 centuries after the end of the Younger Dryas and spanned about 2 centuries (Björck et al., 1996; Hald and Hagen, 1998; Stuiver and Grootes, 2000). Although it has been suggested that the abrupt addition of freshwater responsible for the PBO may have come from the draining of the Baltic Ice Lake (Björck et al., 1996), the PBO also closely follows the 10.1 ka and 9.9 ka ^{14}C yr bursts from Lake Agassiz into the Arctic Ocean (B and C, Table 1); each of these Agassiz outbursts delivered about the same volume of freshwater into the North Atlantic as has been estimated for the Baltic Ice Lake outflow, and thus may have caused or contributed to the PBO. Several factors may help explain why the PBO cooling was not nearly as great as that of the Younger Dryas. First, Lake Agassiz outflow at this time (both the baseline flow and the initial outburst) was northwest into the Arctic Ocean, rather than east into the North Atlantic Ocean. Second, thermohaline circulation may have already entered a more stable interglacial mode from its unstable glacial–interglacial transition mode (Ganopolski and Rahmstorf, 2001). Furthermore, the Gulf of Mexico was no longer receiving glacial meltwater, thus no longer preconditioning North Atlantic THC to change.

Following the diversion of Lake Agassiz overflow into the Great Lakes-St. Lawrence system from its northwesterly route at about 9.4 ka ^{14}C (10.4 ka cal yr), baseline freshwater discharge into the North Atlantic through this route increased by about 0.04 Sv, bringing the total baseline outflow to about 0.15 Sv (Licciardi et al., 1999) (Fig. 2); outbursts associated with lake stages D, E, F, G, H, and I, which ranged from 0.05–0.22 Sv if occurring over 1 year, were superposed on this baseline flow. Using an isotopic model, Moore et al. (2000) estimate that baseline flow through the St. Lawrence Valley and from the southeastern LIS during this time varied from about 0.025–0.12 Sv. Clark et al. (2001) correlate the outburst around 9.4 ka ^{14}C yrs, reported by Leverington et al. (2000) (D in Table 1), to a short reduction in formation of NADW indicated in the δ^{13}C of marine core VM29–191. Overall, however, freshwater outbursts of this magnitude do not appear to have had a significant impact on THC, ocean sedimentation, nor the Greenland ice cap during the two millennia following the PBO, although some climate variation is indicated in North Atlantic deep sea cores (Bond et al., 1997) and there are some small increases in terrestrial ions and sea salts in the Greenland ice cores that have been associated with colder conditions (O'Brien et al., 1995) as well as a few negative δ^{18}O spikes (Grootes and Stuiver, 1997).

Alley et al. (1997) described a widespread cold event recorded in the Greenland GISP2 ice core, oceans, and elsewhere around the North Atlantic at 7.7–7.2 ka ^{14}C yrs (8.4–8.0 ka cal yr), and suggest that an influx of freshwater through Hudson Strait may have been responsible. Barber et al. (1999) and Clark et al. (2001) conclude that this event is related to the final outburst from amalgamated Lakes Agassiz and Ojibway. This outburst through Hudson Strait was in addition to an increase in baseline flux of >0.1 Sv over a 700 year period after 7.7 ka ^{14}C BP (Licciardi et al., 1999). If all of this lake drained in 1 year, 5.2 Sv of new freshwater would have reached the North Atlantic Ocean via Hudson Strait (Fig. 2). Alternatively, as previously discussed, this Agassiz–Ojibway outburst may have occurred in two steps, which would have added an initial 3.6 Sv to the outflow to the North Atlantic (for a period of 1 year) and another 1-year outburst of 1.6 Sv shortly afterward.

Regardless of which scenario is used, the final drainage of the Lake Agassiz–Ojibway superlake abruptly released more than ten times as much freshwater to the North Atlantic as was released from Lake Agassiz at the start of the Younger Dryas (A, Table 1). Although this Agassiz–Ojibway outburst appears to have altered thermohaline circulation (Barber et al., 1999), its relatively small impact probably can be explained by the fact that the ocean was by then in a warm interglacial mode. This, and the fact that all Agassiz outbursts during the previous 1700 radiocarbon years were relatively small (Fig. 2), may explain why there was little variation in ocean circulation and climate around the North Atlantic during this period.

5. Conclusions

The combination of several factors determines whether large but short outbursts of freshwater impacted on THC, including: (1) volume, (2) flux, (3) geographic location of inflow, and (4) whether ocean circulation was in a glacial, interglacial, or transitional mode. Supplemental additions of water from icebergs, diversions of continental drainage systems, or other lake bursts (e.g. from the Baltic Ice Lake), either concurrently or sequentially, may play a role by either supplementing this initial outburst and/or by sustaining the length of the influx, albeit at a much reduced flux. In North America, Lake Agassiz was the only lake that is known to have abruptly released huge volumes of stored water. The larger outbursts ranged from about 1600–163,000 km^3, and temporarily resulted in at least a doubling of outflow from its drainage basin. Because the largest outbursts were 5.6–52 times the baseline outflow, it seems likely that they were a key component in altering THC.

We conclude that significant changes in ocean circulation during a glacial–interglacial transition mode may have come about when the short-term (outburst) volume and flux of the freshwater additions were $<10{,}000\,km^3$ and/or 0.30 Sv or less (e.g. at start of the Younger Dryas). However, once circulation of the North Atlantic Ocean entered an interglacial mode, an outburst of $163{,}000\,km^3$ in 1 year (5.2 Sv) only brought about a modest response in THC (i.e. the 8.2 ka Agassiz–Ojibway cooling event). Of course part of the explanation may be that the influx from Lake Agassiz–Ojibway during the relatively small 8.2 ka ocean/climate perturbation was directed into the North Atlantic via Hudson Strait, nearly 2000 km to the north of where Agassiz outflow had entered the ocean at the start of the Younger Dryas.

We conclude that the role of some short-term outbursts from glacial Lake Agassiz probably provided a critical component in the complex history of ocean circulation and associated climate change during the last deglaciation, at times pushing an already weakened THC over the threshold. Outbursts at 10.9 ka ^{14}C yrs (at the start of the Younger Dryas), 10.1 and 9.9 ka ^{14}C yrs (near the start of the Preboreal Oscillation), and 7.7 ka ^{14}C yrs (at the start of the 8.2 ka cal yr cooling) seem to have impacted on thermohaline circulation, and coincided with the start of significant climate cooling events. In fact, throughout the Quaternary, outbursts from predecessors of Lake Agassiz, perhaps in combination with shifts in the routing of runoff from North American cryohydrological basins, may have destabilized or shut down the NADW conveyor belt (Teller, 1995; Clark et al., 2001).

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