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Preboreal oscillation caused by a glacial Lake Agassiz flood

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Abstract

The Preboreal oscillation (PBO) has been attributed to increased meltwater, but the source of the meltwater and causative mechanism of the PBO has remained elusive. Here we attribute the source to a massive meltwater discharge event from an abrupt drainage of glacial Lake Agassiz, Canada, via the Mackenzie River into the Arctic Ocean. A maximum volume of 21,000 km^3 was discharged over a 1.5–3 yr period with a peak discharge of 0.500 Sverdrups (Sv), equivalent to a 6 m rise in the Arctic Ocean (or 0.062 m rise in global sea level). The flood occurred at about 11,335 cal yr BP, and was followed by a $\sim$0.042 Sv flow until 10,750 cal yr BP when the southern outlet of Lake Agassiz reopened and diverted drainage to the Mississippi River system. We estimate that only 2–4% of the flood water would have frozen into sea ice within the Beaufort region, but coupled with increased river ice production during winter, and thicker pack ice growth throughout the Arctic Ocean, a thicker, longer lasting and more extensive pack ice may have been flushed through Fram Strait. The thicker and more extensive pack ice, and freshened sea surface, may have triggered the PBO by increasing albedo, and generating a low salinity anomaly upon melting in the North Atlantic, thus decreasing the formation of North Atlantic Deep Water.

1. Introduction

The Preboreal oscillation (PBO), a brief (150–250 yr) cooling event that began at 11,300 cal yr BP, is widely recognized in high-resolution climate records from the North Atlantic region (Johnson et al., 1992; O'Brian et al., 1995; Björck et al., 1996, 1997; Hald and Hagen, 1998). An increase in freshwater to the North Atlantic causing a reduction in the thermohaline circulation, has been proposed as the cause of the PBO (Björck et al., 1996; Hald and Hagen, 1998), but the source of that freshwater remains uncertain. Multiple, high-magnitude discharges of freshwater from the Baltic Sea basin predate the PBO (Björck, pers. comm., 1995; Boden et al., 1997). Hald and Hagen (1998) concluded that the PBO was caused by an increased flux of meltwater to the Nordic Seas from adjacent ice sheets in response to post-Younger Dryas warming. This hypothesis, however, does not explain why the event was short-lived, nor why subsequent similar events did not occur while ice sheets remained in the region.

Here we argue that the origin of the PBO was associated with a large, but short-lived, increase in freshwater discharge to the Arctic Ocean resulting from an abrupt drainage and lowering of Lake Agassiz when deglaciation uncovered the northwest outlet to the Mackenzie drainage basin. We propose that the increased discharge and increased production of river ice and sea ice in the Arctic Ocean was then exported to the North Atlantic causing the PBO.

2. The Lake Agassiz connection

Glacial Lake Agassiz, which formed along the southwestern margin of the retreating Laurentide Ice Sheet (Teller et al., 1983) discharged meltwater either south to the Gulf of Mexico, east to the North Atlantic Ocean, or north to the Arctic Ocean (Fig. 1). Flow from the northwest Agassiz outlet to the Arctic via the Mackenzie River is our hypothesized meltwater source that indirectly initiated PBO cooling. Investigations of the northwest outlet (Smith and Fisher, 1993; Fisher and Smith, 1994; Fisher and Souch, 1998) suggest that it opened at 11,250 cal yr BP (9900 ^{14}C BP) shortly after closure of the eastern outlets, which was at 11,450 cal yr BP (10,025 ^{14}C yr BP; Lowell et al., 1999).

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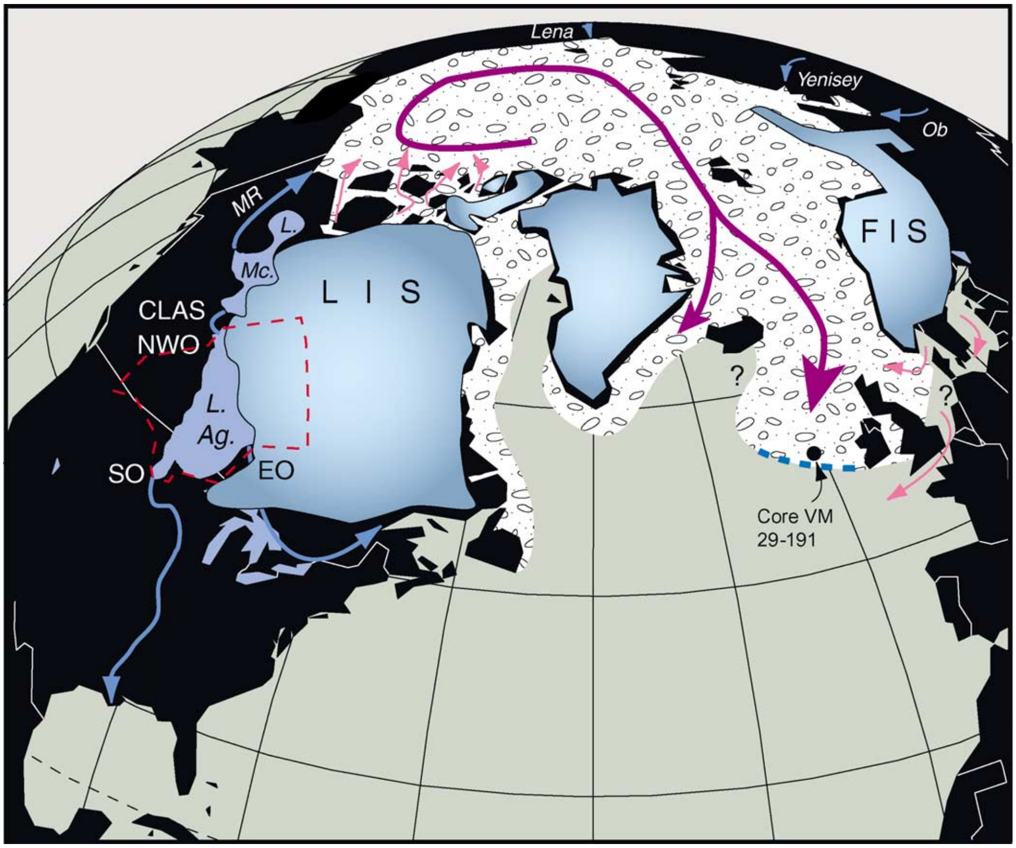

Fig. 1. Teleconnection between glacial Lake Agassiz and the North Atlantic. The release of stored meltwater into the Arctic Ocean from Lake Agassiz (L. Ag) would have resulted in a substantial increase in pack ice. The flood was buffered by glacial Lake McConnell (L. Mc) before passing through the Mackenzie River (MR). Due to the clockwise circulation of the Beaufort Gyre, the increased extent of sea ice entered the North Atlantic (purple arrow). Dashed blue line is possible southern extent of icebergs as indicated by IRD from core VM 29–191 (Bond et al., 1997). Dashed red lines indicate increased drainage area of the Mackenzie River. Pink arrows indicate direction of meltwater flow. Representation of the Laurentide Ice Sheet (LIS) and of the Fennoscandinavian Ice Sheet (FIS) is based on the 'minimum' model of Lambeck (1995).

The northwest outlet opened when an earthen drainage divide was overtopped and incised, causing the lake level to lower by 52 m (Smith and Fisher, 1993) forming the Clearwater-lower Athabasca spillway (CLAS, Fig. 1). The outlet then stabilized at a series of bedrock channels 100 km southeast of CLAS (Fisher and Souch, 1998). The 150 km long spillway ends at the Late Pleistocene Athabasca braid delta (LPABD) that built into glacial Lake McConnell (Smith, 1994). Fisher (1993) used a variety of methods to determine the paleovelocity in the CLAS and calculated a range of values from 6.3 to 28.9 $\mathrm{m\,s^{-1}}$ with 12 $\mathrm{m\,s^{-1}}$ being a reasonable estimate. Using the flow continuity equation where discharge (Q) = cross-sectional area (A) $\times$ velocity (V); with $A = 180{,}000\,\mathrm{m^2}$ (assuming bankfull conditions of 1800 m width and 100 m depth for the reach immediately east of Fort McMurray, Alberta) and $V = 12\,\mathrm{m\,s^{-1}}$, a peak discharge of 2.160 Sv (1 Sverdrup = $10^6\,\mathrm{m^3\,s^{-1}}$) is calculated. Using the same methodology, a peak discharge of 0.500 Sv was calculated for the outflow of water from Lake McConnell into the Mackenzie River (width = 6200 m, depth = 37 m, velocity = 2.2 $\mathrm{m\,s^{-1}}$ at bankfull) indicating that Lake McConnell likely had a cushioning-effect on the flood from Lake Agassiz.

Estimates of the volume of water released from the northwest outlet depend upon the paleobathymetric estimates for the area and volume of Lake Agassiz immediately prior to opening of the northwest outlet. These estimates are variable, reflecting uncertainties in the size of the lake. Estimates range from 440,000 $\mathrm{km^2}$ and 42,340 $\mathrm{km^3}$ (Fisher and Smith, 1994) to 350,000 $\mathrm{km^2}$ and 38,000 $\mathrm{km^3}$ (Mann et al., 1999) to 263,000 $\mathrm{km^2}$ and 22,700 $\mathrm{km^3}$ (Leverington et al., 2000). The later two estimates are smaller because they did not include an approximate 70,000 $\mathrm{km^2}$ northwest extension of the lake based on mapped strandlines and glaciolacustrine sediment described by Fisher and Smith (1994). Fisher (1993) calculated that 21,000 $\mathrm{km^3}$ of water was released out the northwest outlet in a catastrophic flood by averaging two volumes determined from lake areas before and after the 52 m drop in lake level

$(440{,}000\,km^2 \times 0.052\,km) + (370{,}000\,km^2 \times 0.052\,km)/2)$. The 440,000 km^2 lake area was constrained by the uppermost strandlines at the northwest outlet (Fisher and Smith, 1994), and the 370,000 km^2 lake area is known from the Teller et al. (1983) map. Leverington et al. (submitted, pers. comm. 2001) suggest that only 11,600 km^3 of water was released, which provides a minimum value for our calculations.

The flood durations can now be estimated. Assuming an instantaneous peak discharge of 2.160 Sv in the CLAS, and a minimum and maximum available volume of 11,600 and 21,000 km^3, respectively, calculations yield 62 and 113 day flood durations from Lake Agassiz to Lake McConnell. The subsequent drainage from Lake McConnell to the Arctic Ocean at 0.500 Sv would require a minimum of 201 days or a maximum of 486 days. These durations should be considered minimum estimates because peak discharges would not be maintained during the entire flood as rates would decrease with lowered lake levels, and the outflow volume from Lake McConnell would exceed Agassiz inflow volume due to outlet incision. A reasonable estimate of the flood duration from Lake Agassiz to the Beaufort Sea is about 1.5 yr but may have been twice that (because only peak discharges were used in the calculations), during which up to 21,000 km^3 of water was added to the $\sim$0.042 Sv base flow (Licciardi et al., 1999) of the Mackenzie River. After the 1.5–3 yr northwest outlet catastrophic flood (0.222–0.444 Sv), an additional $\sim$0.042 Sv (Licciardi et al., 1999) of water from Lake Agassiz was added to the Arctic Ocean from the Lake Agassiz basin while the northwest outlet remained open.

Four radiocarbon dates from the CLAS and LPABD (Fig. 2) average 11,275 cal yr BP (Table 1). The formation of the CLAS and much of the LPABD are assumed to be synchronous because of their similar scale and lack of reworking by subsequent flow. Meltwater from Lake Agassiz continued to be routed to the northwest until 10,750 cal yr BP (Fisher and Yansa, 2001) when isostatic rebound raised the outlet, forcing flow to the south (Fisher and Souch, 1998). The average age of the flood (11,335 cal yr BP) and delta deposits (11,215 cal yr BP) is similar to the onset of the PBO at 11,300 cal yr BP.

3. PBO cooling mechanism

Our proposed PBO cooling mechanism for disrupting North Atlantic Deep Water (NADW) formation is the increased supply of meltwater from Lake Agassiz to the Arctic Ocean, and subsequent export of sea ice and fresher water to the North Atlantic. The additional input of 21,000 km^3 of water over 1.5–3 yr would have reduced surface water salinity in the Arctic Ocean and North Atlantic. Reduced salinity surface waters have higher freezing temperatures, promoting stratification and sea-ice growth. Tremblay and Mysak (1998) developed a dynamic-thermodynamic sea-ice model to understand variations in sea-ice thickness in response to increased runoff in the Beaufort Sea area. They determined that runoff anomalies have a small effect on sea-ice anomalies; for example, an 8% (50 km^3) increase in Mackenzie River discharge results in a 4% increase in ice thickness, which they considered insignificant to explain the observed sea-ice anomalies. In comparison, 3500 km^3 of freshwater enters the Arctic Ocean each year, of which the Mackenzie River contributes on average 340 km^3 (Aagaard and Carmack, 1989). Our estimate of up to 21,000 km^3 of water is 5 times the present total freshwater input. Using the Tremblay and Myask model, a flood of 21,000 km^3 over 3 yr, would increase first-year sea-ice thickness in the Beaufort Sea by 44%. After the initial flood and while

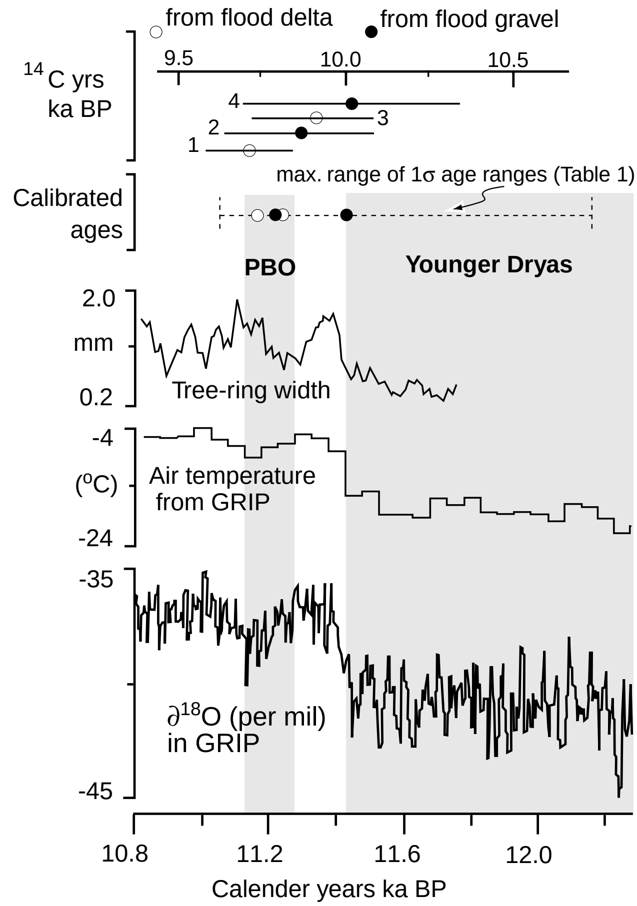

Fig. 2. Association of radiocarbon ages from flood gravel and flood delta associated with opening of the northwest outlet of Lake Agassiz. The flood gravel and lower delta sediments are hypothesized to have been deposited during the initial flood which lowered the lake by 52 m over approximately 3 yr initially discharging between 11,600 and 21,000 km^3 into glacial Lake McConnell. Calibration of the ^{14}C dates is from CALIB 4.3 (Stuiver et al., 1998). The dates are clustered immediately at the onset of the PBO. Tree ring and GRIP data modified from Björck et al. (1996).

Table 1
Radiocarbon dates

Sample[a]	Lab. #	Material	^{14}C age (^{14}C yr BP $\pm 1\sigma$)	Cal. age (cal yr BP)	1σ range (cal yr BP)[b]
FD1	Gx-5036-I	Wood	$10{,}015 \pm 320$	11,440[c]	12,164–11,161
FD2	GX-5031-I	Wood	9860 ± 230	11,230	11,699–11,063
D1	GSC-4302	Wood	9910 ± 190	11,260	11,749–11,150
D2	AECV-1183C	Wood	9710 ± 130	11,170	11,227–11,060

[a] FD—flood deposits; D—delta deposits.
[b] Calibrated age determined from CALIB V4.3 (Stuiver et al., 1998).
[c] Mean age from multiple slope intercepts (^{14}C vs. calendar BP).

the NW outlet remained open, an increased discharge (0.042 Sv) would increase first-year sea-ice thickness by 34%. Although our calculations indicate only 2–4% of the Agassiz meltwater entering the Arctic Ocean is converted to sea ice in the Beaufort region, the meltwater plume mixing in areas of open water or stratifying the water column beneath pack ice, would cause thicker sea ice beyond the Beaufort region while the northwest Agassiz outlet was open. Not included in these estimates is river ice forming in transit from Lake Agassiz during the winter seasons.

Sea level at the beginning of the PBO was still 10–15 m lower than the Bering land bridge (Fairbanks, 1989; Bard et al., 1996), and the grounded Innuitian Ice Sheet clogged channel flow between the Canadian Arctic Islands (Dyke, 1999; England, 1999), forcing water and sea ice into the North Atlantic via the Fram Strait and East Greenland Current. Conceivably the thicker sea ice in the Arctic Ocean may have led to an increase in the volume and lateral extent of sea ice exported to the North Atlantic, increasing albedo, altering atmospheric circulation, and upon melting, freshening surface water.

4. Discussion

Previous attempts at explaining the PBO have focused on meltwater sources in the Nordic regions. In modeling studies, excess meltwater delivery of between 0.06–0.12 Sv reduces the formation of Labrador Sea Intermediate Water and NADW (Rahmstorf, 1996; Fanning and Weaver, 1997; Manabe and Stouffer, 1997). For approximately 200 years after the Younger Dryas, meltwater entered the North Atlantic from the Nordic region without causing a cooling, including large volumes of meltwater from the Baltic Ice Lake (Boden et al., 1997). Rather than causing the PBO, meltwater from the Nordic regions may have played an important role in preconditioning the North Atlantic for 200 years. Fanning and Weaver (1997) modeled a short time lag (within 200 yrs) when modeling Younger Dryas climate change in response to a temporal and geographical meltwater input using Teller's (1990) 500 yr time slices of meltwater routing. A similar preconditioning may have occurred from Fennoscandinavian Ice Sheet meltwater, and eastern outlet Agassiz meltwater before the northwest outlet "trigger" event.

We hypothesize that the "trigger" event for reducing the thermohaline circulation and causing the PBO was the short-lived (1.5–3 yr) catastrophic flood into the Arctic Ocean from glacial Lake Agassiz. However, the PBO lasted from 150–250 yr, and with our hypothesis, some mechanism must have existed to maintain a reduced thermohaline circulation system for that time frame. Licciardi et al. (1999) calculated that 0.042 Sv was contributed by Lake Agassiz to the Arctic Ocean, or 4.4 times that of the modern Mackenzie River. We suggest that the advection of thicker sea ice and a fresher East Greenland Current to the North Atlantic was sufficient to maintain the reduced ventilation between surface and deep water initiated by the trigger event. During the Preboreal, isostatic recovery in Lake Agassiz was greatest at the northwest outlet sill (Fisher and Souch, 1998), resulting in transgression and meltwater storage throughout the lake basin. As a result, the water supply from Lake Agassiz would slowly diminish during the PBO at a time when less meltwater would also be expected from cooling in the Nordic regions.

A recent analog for our proposed Arctic Ocean expanding sea-ice model may be the "Great Salinity Anomaly" (GSA) of the 1960s and 1970s (Dickson et al., 1988; Mysak and Power, 1991; Serreze et al., 1992). Although the specific origin of this event remains elusive, there is agreement that it was associated with an increased export of sea ice out of the Arctic Ocean via the Fram Strait. The track of this freshwater plume (Belkin et al., 1998) entered the North Atlantic via the Denmark Strait and led to a reduction in convection in the Labrador Sea (Dickson et al., 1996). This event was especially marked off northern Iceland (Tremblay and Mysak, 1998). We suggest that both GSA events are modern analogs (but on a small scale) of the PBO.

Our hypothesis differs from that of Björck et al. (1996) and Hald and Hagen (1998) by incorporating sea-ice volumes along with increased meltwater supply. We speculate that with a significantly thicker (34–44%) first-year pack ice leading to a longer-lasting sea-ice cover, a stronger anticyclone may have persisted over the Arctic basin, setting up stronger winds and currents within the Beaufort Gyre that fed the Transpolar Drift Stream forcing ice out of the Arctic via Fram Strait. The southward-moving pack ice entering the North Atlantic would have increased albedo, cooled the ocean surface and adjacent landmasses, and weakened the thermohaline circulation system upon melting.

We conclude that the PBO was triggered and maintained by an expanding sea ice and lower-salinity surface water moving southward from the Arctic Ocean into the North Atlantic, rather than by just an increased flux of meltwater from the Nordic region. The increased sea ice production was initiated by catastrophic drainage from Lake Agassiz resulting in first-year ice up to 44% thicker and delivery of fresh water to the Arctic Ocean. Most compelling are our radiocarbon dates that averaged 11,275 cal yr BP for the Agassiz flood that corresponds closely in age with the onset of the PBO at 11,300 cal yr BP. The 150–250 yr PBO cooling was maintained by the positive sea-ice anomalies and increased meltwater from the 60% enlarged Mackenzie River drainage basin. Cessation of the PBO was a result of the gradual abandonment of the NW outlet of Lake Agassiz, and/or an overall diminishing supply of sea ice and meltwater to the North Atlantic from the Arctic Ocean and Nordic regions.

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