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Review Article

Lake Agassiz during the Younger Dryas

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ABSTRACT

Lake Agassiz was ponded on the northward-sloping surface of the Hudson Bay and Arctic Ocean basins, as the Laurentide Ice Sheet retreated. The level of Lake Agassiz abruptly fell ~12.9 cal (11 ^{14}C) ka BP, exposing the lake floor over a large region for >1000 yr. The routing of overflow during this (Moorhead low-water) period is uncertain, and there is evidence on the continent and in ocean basins for both an easterly route through the Great Lakes–St. Lawrence to the North Atlantic and for a northwesterly route through the Clearwater–Athabasca–Mackenzie system to the Arctic Ocean. The Moorhead low water phase coincides with the Younger Dryas cooling, and a cause–effect relationship has been proposed by attributing a change in ocean thermohaline circulation to the re-routing of Lake Agassiz freshwaters from the Gulf of Mexico to more northern oceans. Paleoclimatic interpretations from ecosystems in lake sediments in the region, and a simple calculation of the paleohydrological budget of Lake Agassiz, indicate that the climate remained wet and cool throughout the YD in this region, and was not warm nor dry enough to allow evaporative loss to offset the influx of meltwater and precipitation; thus, the Moorhead phase resulted from changes in the outlet that carried overflow.

Introduction

Lake Agassiz was the largest lake in the world for thousands of years (Fig. 1), covering an area of as much as 841,000 km^2 along the margin of the Laurentide Ice Sheet (LIS) (Leverington et al., 2002). Although the overall level of Lake Agassiz at any one place declined through time, there were many fluctuations during its 5000 yr history and its size varied substantially. Many summaries of the lake's history have been published (e.g., Upham, 1895; Elson, 1967; Teller and Clayton, 1983; Teller, 1985; Teller and Leverington, 2004), although they differ in detail. Lake fluctuations were controlled by the opening and closing of overflow channels as a result of the location of the LIS margin, outlet erosion, and isostatic rebound. Abrupt drops in lake level were followed by relatively slow rises that lasted decades to centuries (e.g., Elson, 1967; Teller, 2001; Teller and Leverington, 2004). Many strandlines (beaches and wave-eroded scarps) formed as a result of these lake-level fluctuations, mainly by abrupt regressions that stranded beaches at the end of a transgressive phase of the lake (e.g., Leverett, 1932; Johnston, 1946; Elson, 1967; Teller, 2001; Teller and Leverington, 2004); some beaches resulted from storms (McMillan and Teller, 2012).

The largest drop in lake level, prior to its final drainage into Hudson Bay, was around 12.9 cal (11 ^{14}C) ka BP, when its Southern Outlet (S in Fig. 1) was abandoned for lower routes to the north (e.g., Fenton et al., 1983). This led to formation of the Moorhead low-water unconformity in the Lake Agassiz lacustrine sequence. Following this, the lake remained at low levels for at least a thousand years—vegetation grew on this surface of the lake floor and river channels were incised.

The subsequent deepening of Lake Agassiz (transgression) from its Moorhead low-water phase was the result of differential isostatic rebound of the outlet and/or a readvance of the LIS over the outlet (e.g., Elson, 1967; Clayton, 1983; Fenton et al., 1983; Teller, 2001). Lake Agassiz reached its maximum post-Moorhead phase expansion at the Campbell strandline around 10.6 cal (9.4 ^{14}C) ka BP, and began overflowing again through its Southern Outlet (Teller et al., 2000; Fisher et al., 2008a), thus ending the Moorhead phase of the lake.

During the next thousand years, lower outlets were opened as the LIS retreated northward, each time allowing water levels to abruptly drop. While each outlet was in use, differential isostatic rebound raised its elevation, causing lake levels to transgress southward until the LIS retreated far enough to open a new and lower outlet. About 8.4 ka, the LIS dam across the Hudson Bay Lowlands failed and Lake Agassiz drained abruptly, perhaps in two stages (Barber et al., 1999; Teller et al., 2002; Clarke et al., 2004).

Lake Agassiz and its Younger Dryas link to global change

The Younger Dryas (YD) cool period has been the subject of considerable discussion in the past 20 years. The abrupt return to cooler conditions across a large region of the globe during the YD, especially in the circum-Atlantic region, during a period when post-glacial warming had long been underway, has been a challenge to explain.

Rooth (1982) and Johnson and McClure (1976) suggested that the addition of freshwater into the "Gulf Stream" of the North Atlantic might have interrupted the northward transport of warm water into

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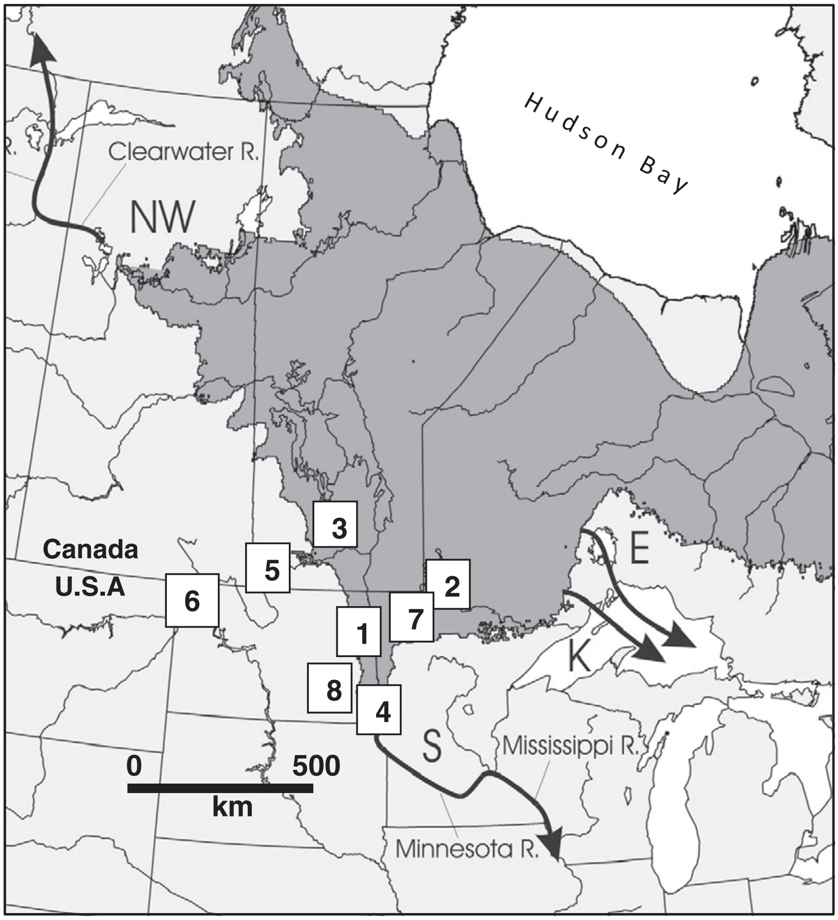

Figure 1. Area covered by Lake Agassiz during its 5000-yr history (dark gray); arrows show overflow routes through its Southern Outlet (S), Northwestern Outlet (NW), and Eastern Outlets (K and E). (after Leverington and Teller, 2003) Numbers in boxes refer to sites discussed in this paper.

high latitudes. Broecker et al. (1985, 1988) elaborated on this idea, and Broecker et al. (1989) proposed that Lake Agassiz may have been the source of the freshwater during the YD. The basis of this hypothesis centered on the coincidence of the abrupt draw down of the level of Lake Agassiz around 12.9 cal (11 ^{14}C) ka BP—when its overflow was diverted away from its southern routing to the Gulf of Mexico to an eastern outlet —and the continuation of that eastward overflow into the Great Lakes–St. Lawrence to the North Atlantic Ocean for about a thousand years. The abrupt diversion of meltwater away from the Mississippi River was noted in dated cores in the Orca Basin of the Gulf of Mexico and attributed by Broecker et al. (1989) to the easterly re-routing of Lake Agassiz.

Geomorphic and sedimentological information from the region where Lake Agassiz overflowed into the Superior basin provided further support for this hypothesis. Teller and Thorleifson (1983, 1987) described extensive deposits of boulder gravel in that region (E in Fig. 1), and landforms that were similar to those found in the Channelled Scabland in the northwestern U.S., which had formed by catastrophic outbursts from an ice-marginal lake (e.g., Bretz, 1969; Baker and Bunker, 1985). Alley (2007) discussed this hypothesis, championed by Wally Broecker, stating that it has “gained a widespread acceptance” and spawned research that “opened new disciplines, including the nascent field of abrupt climate change, provided important insights to climate processes, feedbacks, and sensitivity, and captured public as well as scientific attention” (p. 142). Alley adds that there are still some skeptics, but the paradigm of interrupting thermohaline circulation by freshwater has a “predictive power” that has been tested and borne out.

Thus, given the chronology in the Lake Agassiz basin that was known at the time the hypothesis was proposed, there seemed to be a cause–effect relationship between the thousand-year-long Younger Dryas cooling centered on the North Atlantic and the catastrophic overflow from Lake Agassiz and the sustained eastward diversion of runoff from a two million km^2 region of North America. Subsequent ocean–atmosphere modeling of the impact of a large and abrupt addition of freshwater to the North Atlantic at the mouth of the St. Lawrence Valley seemed to confirm the link (e.g., Rahmstorf, 1995; Fanning and Weaver, 1997; Manabe and Stouffer, 1997; Rind et al., 2001).

For more than a century researchers considered the diversion of Lake Agassiz overflow away from the Southern Outlet to have been eastward into the North Atlantic Ocean via the Lake Superior basin, through the Great Lakes, and into the St. Lawrence Valley, and to have been the result of ice retreat from the Superior basin (Fig. 1) (e.g., Upham, 1895; Johnston, 1916; Elson, 1967; Fenton et al., 1983; Teller and Thorleifson, 1983; Teller, 1990; Licciardi et al., 1999; Carlson and Clark, 2012). However, a recent study by Lowell et al. (2009), based on cored and dated sequences, concluded that the eastern outlet of Lake Agassiz into the Superior basin was not opened until after 12.1 cal (10.3 ^{14}C) ka BP, long after the Moorhead low-water phase had begun. A study by Teller et al. (2005), based on dated cores and stratigraphic sequences in the eastern outlet region also found no chronological support for opening the eastern outlets until after 11.7 cal (10.1 ^{14}C) ka BP, and suggested that the YD diversion of Lake Agassiz may have been to a lower outlet in the northwestern corner of the basin that carried overflow through the Clearwater–Athabasca–Mackenzie river basin to the Arctic Ocean (NW in Fig. 1), rather than into the Great Lakes; this routing had previously been identified (Elson, 1967; Zoltai, 1967; Teller and Thorleifson, 1983; Smith and Fisher, 1993; cf. Upham, 1895, 231–32). Recent OSL

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dating of flood sediments at the mouth of the Mackenzie River (Murton et al., 2010a), modeling by Tarasov and Peltier (2005, 2006), and more recent fine-scale point source modeling by Condron and Winsor (2012) have concluded that a large influx of freshwater into the Arctic Ocean and, in turn, into the North Atlantic could have been responsible for the YD cooling.

As described in the next section, convincing evidence has not been presented for which of these two routes was used for Lake Agassiz overflow during the YD, so debate continues (see Teller et al., 2005; Fisher et al., 2006; Teller and Boyd, 2006; Fisher et al., 2009; Murton et al., 2010a; Carlson and Clark, 2012; Fisher and Lowell, 2012; Voytek et al., 2012), with some arguments calling on evidence “downstream” from the Agassiz basin in the Arctic Ocean (e.g., Hall and Chan, 2004; Polyak et al., 2007; Maccali et al., 2012; Not and Hillaire-Marcel, 2012) and in the St. Lawrence Valley-North Atlantic (e.g., deVernal et al., 1996; Clark et al., 2001; Carlson et al., 2007; Carlson and Clark, 2012; Cronin et al., 2012).

The Moorhead phase and routing of Younger Dryas overflow from Lake Agassiz

Figures 2A and 2B show the extent of Lake Agassiz prior to the 12.9 ka drawdown to the Moorhead low-water phase, and immediately after it. The volume loss from this drawdown was calculated as 4900 km^3, and the extent of the lake decreased from 184,000 km^2 to 117,000 km^2 (Leverington et al., 2000). Buried and reworked organics from the newly exposed floor of the lake basin indicate that vegetation had colonized it within a century or two (see Fisher et al., 2008a). These organisms are now buried by subsequently deposited lacustrine sediment and are a good record of environmental conditions on the exposed lake floor at that time. These organics have been reported in a number of publications (e.g., Ashworth and Cvancara, 1983; Upham, 1895; Teller et al., 2000), but the most detailed investigations come from Bajc et al. (2000) and Fisher et al. (2008a). As elaborated in a later section, at sites where the Moorhead phase has been dated, many flora and fauna have been identified, including many species of trees, shrubs, herbs, grasses, emergent plants, insects, arachnids, and shelled organisms that thrived in this newly exposed lake floor environment. In addition, Ashworth and Cvancara (1983) summarized the fossil evidence in the southern Lake Agassiz basin from 29 sites, most from the Moorhead phase interval, which include vertebrates, molluscs, and insects. Rivers incised their channels across the floor of the southern Lake Agassiz basin at this time (Arndt, 1977), and a weak soil developed (Rominger and Rutledge, 1952), before the basin was again submerged by rising Lake Agassiz waters.

Teller et al. (2005) summarized the arguments for and against eastward overflow from Lake Agassiz, noting that “Warman (1991), Minning et al. (1994), Thorleifson (1996), and Teller and Leverington (2004) have raised questions about an eastward routing between 11 and 10 ^{14}C ka”. However, until recently, “the unanimous conclusion of researchers has

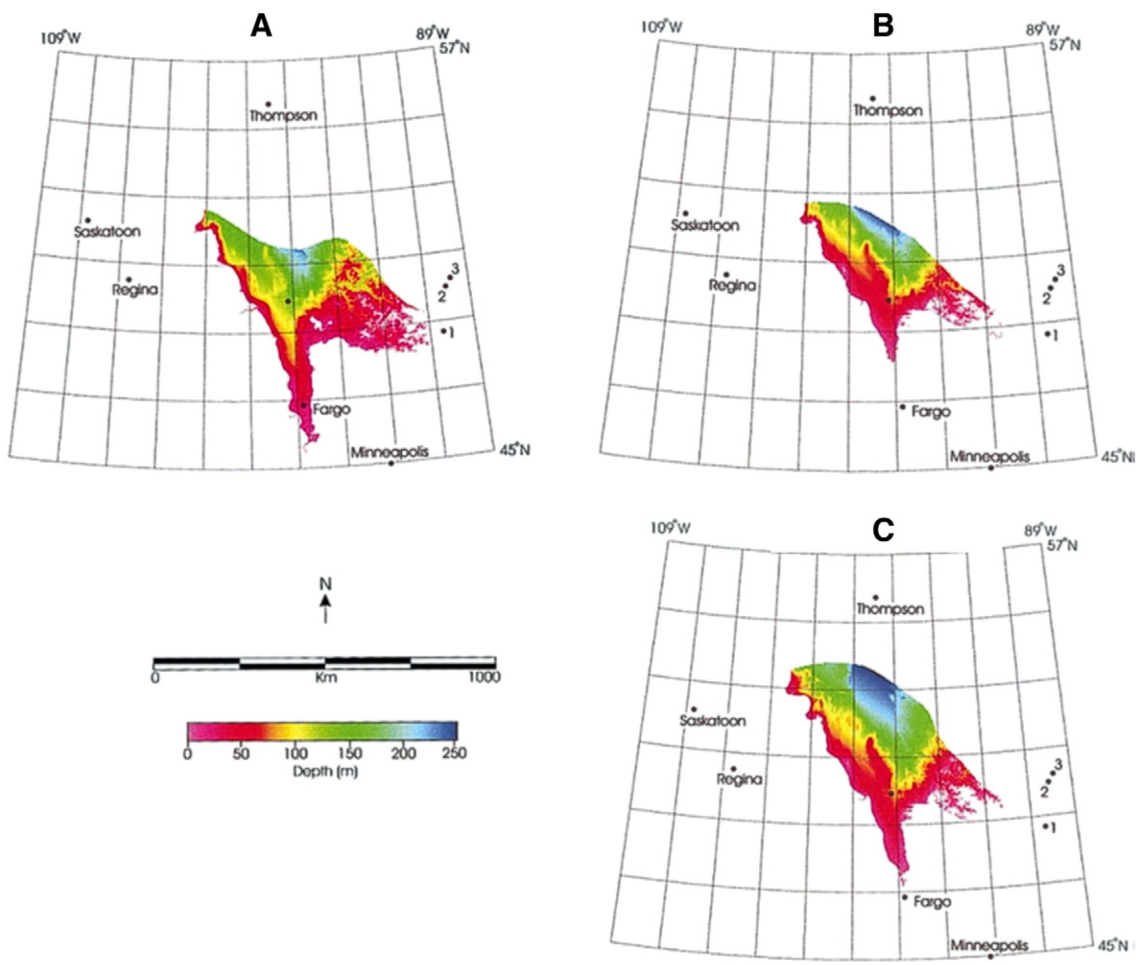

Figure 2. Bathymetry of Lake Agassiz at 3 times: A) Tintah beach level just before YD draw down of lake; B) Moorhead low-water level just after abrupt drop from Tintah beach; C) Upper Campbell beach level at end of YD transgression (after Leverington et al., 2000, Fig. 3). Paleotopography of the basin was constructed using the GLOBE data base adjusted for differential isostatic rebound mapped from isobases determined from paleobeach elevations. Note that the extension of Lake Agassiz to the Northwestern Outlet as shown in Fig. 1 was not included in this earlier reconstruction. The location of Thunder Bay, Ontario, and the K outlet of Fig. 1 into Lake Superior is indicated by 1, and two pathways into Lake Nipigon (E in Fig. 1) are shown by 2 and 3. Dot in center of Lake Agassiz basin at 97.3°W and 49.8°N is the city of Winnipeg.

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been that, even though the northwestern outlet region was below the elevation of the eastern outlets at Thunder Bay…the Laurentide Ice Sheet (LIS) blocked all northwestward drainage until about 10 ^{14}C ka, when retreat opened the Clearwater–Athabasca Valley route to the Arctic Ocean (Christiansen, 1979; Schreiner, 1983, 1984; Dyke and Prest, 1987; Fisher and Smith, 1994; Fisher et al., 2002; Dyke, 2004)" (p. 1892). Teller et al. (2005) also elaborated on research that had raised concerns about the absence of a freshwater signal in the St. Lawrence Valley, including that of dinoflagellates (deVernal et al., 1996) and benthic foraminifera (Rodrigues and Vilks, 1994), and δ^{18}O in *Neogloboquadrina pachyderma* off the mouth of the St. Lawrence Valley (Keigwin and Jones, 1995). On the other hand, Carlson et al. (2007) used Mg and U relative to the Ca in planktonic forams to argue that sediments deposited in the St. Lawrence estuary during the YD must have come from the Agassiz basin. Cronin et al. (2012) used ostracodes, foraminifera, and their oxygen isotope record in the St. Lawrence Valley to argue in favor of an easterly route for Lake Agassiz overflow at the start of the YD. Carlson and Clark (2012, p. 47–49) summarize arguments for the eastward routing of North American runoff to the St. Lawrence during the YD, and describe concerns about a northwest routing from the Lake Agassiz basin. Some studies (e.g., Rodrigues and Vilks, 1994; Cronin et al., 2008) indicated that an influx of freshwater into the St. Lawrence, perhaps from Lake Agassiz, began during the YD, not at the start.

In the Agassiz basin, supporting YD overflow from Lake Agassiz into the Great Lakes is the presence of a series of red-colored varves in the gray varved sequence of Lake Agassiz in northwestern Ontario (Rittenhouse, 1934; Antevs, 1951; Zoltai, 1961; Teller and Thorleifson, 1983), with a chemical composition similar to that in the Superior basin, where red-colored bedrock and sediment are common (Warman, 1991; Minning et al., 1994). Researchers have concluded that these red varves indicate that overflow between about 12.9 and 11.5 cal (11–10 ^{14}C) ka BP through the eastern outlets of Lake Agassiz was blocked by ice readvancing into the Superior basin and forcing ponded water *westward* over the continental divide; this readvance is documented by a drowned forest bed in the Superior basin dated to about 11.5 cal (10 ^{14}C) ka BP (Clayton, 1983; Drexler et al., 1983; Lowell et al., 1999).

However, evidence for a big YD flood from Lake Agassiz into the Great Lakes through the Eastern Outlets near Thunder Bay, Ontario (K in Fig. 1), as proposed by Teller and Thorleifson (1983), is far from convincing. First, it should be noted that the scoured landscape and large boulder fields to the north of Thunder Bay (E in Fig. 1), also originally considered to have been an early route for Agassiz overflow (Teller and Thorleifson, 1983, 1987, and others), formed at a later stage, as convincingly argued by Warman (1991) and Minning et al. (1994) (see also Teller, 2002); only the more southern area (K in Fig. 1) could have carried overflow as early as the YD. In fact, dates from cores in the eastern outlet region are all younger than 10.1 ^{14}C (11.7 cal) ka BP (Teller et al., 2005; Lowell et al., 2009), although many cores did not reach pre-lacustrine sediment or bedrock, so only represent a minimum age of ice retreat and Agassiz overflow. West of Thunder Bay, where the earliest overflow must have occurred if the ice had retreated from the area (Teller et al., 2005), there is an absence of geomorphic landforms and coarse fluvial sediment that would be expected if a rapid drawdown with a large volume of overflow had occurred through that area (Teller and Boyd, 2006; Teller et al., 2005; Lowell et al., 2009). Offshore in the Superior basin from the mouths of valleys in the Thunder Bay region that link the Agassiz and Superior basins there is an absence of coarse sediment that would be expected if there had been a catastrophic outburst from Agassiz and subsequent long period of overflow (Voytek et al., 2012).

Although some of these problems may be explained, including a less-than-catastrophic overflow from Lake Agassiz and a delay after deglaciation in production of organics for dating (Teller and Boyd, 2006), there remains a paucity of evidence for a YD flood through the Eastern Outlets at Thunder Bay (Lowell et al., 2009). Carlson and Clark (2012) argue that there was eastward overflow during the YD, and state that climate model simulations "show that a flood is inconsequential to the forcing of the Younger Dryas, rather requiring a sustained discharge of freshwater to the North Atlantic to suppress AMOC" (p. 51), concluding that the absence of flood features in the eastern outlet near Thunder Bay is not important in assessing overflow routing at this time.

While this absence of YD dates from areas that had to have been deglaciated in order for Lake Agassiz to have overflowed into the Superior basin at that time is perplexing, Teller et al. (2005) and Teller and Boyd (2006) suggested that overflow at this time may have been through the NW outlet during the YD. They noted that a relatively small shift in location of the LIS boundary shown by Dyke (2004) would allow this to happen. Unfortunately, reconstructions of the margin of the LIS are not everywhere well constrained because there are large regions where there are no reliable dates (see Dyke, 2004).

Studies by Fisher et al. (2009) and Fisher and Lowell (2012) in the northwestern part of the Lake Agassiz basin, where 31 cores were taken from lake basins on the uplands as well as in the Athabasca River Valley outlet from Lake Agassiz, showed few dates older than 10 ^{14}C (11.5 cal) ka BP, although the base of the water-laid sequences in 22 cores was not reached, so the record may be incomplete. These researchers concluded that older dates reported in the region (e.g., Anderson and Lewis, 1992; Smith and Fisher, 1993; Teller et al., 2007) do not reflect the true age of deglaciation, unlike Teller and Boyd (2006), Teller (2008, 2012), Teller et al. (2007), Teller and Yang (2009), and Murton et al. (2010a,b), who used stratigraphic and geomorphic evidence, along with the questionable old dates, to argue that overflow from Lake Agassiz may have occurred there during the YD. Fisher et al. (2009) and Fisher and Lowell (2012) summarize the arguments against YD overflow through the NW outlet, as do Carlson and Clark (2012, p. 45–46, 49–50), raising serious questions about that routing, and about where the margin of the LIS was located at that time.

Of course, the absence of YD and older dates in regions around the outlets of Lake Agassiz may be explained as a delay in colonization of the newly deglaciated surface by vegetation (Teller and Boyd, 2006), rather than the presence of ice. This interpretation is supported by the Arctic conditions at that time, especially in the region north of the Northwestern Outlet in the western Keewatin region, although Fisher et al. (2009) argue to the contrary. An analogy may be in the eastern Keewatin region that is known to have been largely ice-free by 7.5 ka, but where there are almost no terrestrial radiocarbon dates that old (Dyke, 2004).

Finally, the absence of dated organics until after the YD could also have been the result of the routing of overflow from Lake Agassiz under the LIS or through a stagnant part of it, such as in the western Keewatin region.

All of this has led to an alternative explanation for the abrupt 50–100 m drawdown of Lake Agassiz at ~12.9 ka. Lowell et al. (2009), Lowell and Fisher (2009), and several abstracts by Lowell and Fisher (e.g., Fisher et al., 2008b; Lowell et al., 2012) have postulated that the lake was lowered by a negative hydrological budget that persisted for more than a thousand years during the YD. Lowell et al. (2012) state that "relatively small changes in hydrologic conditions (e.g., present runoff and precipitation, accompanied by 10–20% increase in evaporation) are sufficient to overcome meltwater contribution". The negative balance simulations are "explained by changes in the location of the polar jet stream, driven by increased arctic albedo" (Lowell et al., 2012). In talks at professional meetings in the past 4 years, it has been argued that this is unlikely (e.g., Teller 2008, 2012). Of course, removal of water from the Agassiz basin by evaporation, rather than by overflow to the oceans, would eliminate the triggering and sustaining role of freshwater from the lake that most have called on to slow thermohaline circulation and, in turn, cool the continents during the Younger Dryas; for this reason, an alternative explanation for the drawdown of this large volume of water needs to be carefully examined if we are to understand the past and future links between freshwater additions to the oceans and climate change.

If this negative hydrological budget is a viable hypothesis, then paleoecological data from the region should provide support for the more arid conditions. As well, the likelihood of having evaporation exceed the influx of water from precipitation and melting of the LIS needs to be examined.

A negative hydrological budget?

Those advocating a negative hydrological budget as an explanation for the rapid drawdown of Lake Agassiz argue that increased evaporation, decreased precipitation, and/or reduced melting of the LIS led to more water loss from the basin than gain—in other words, a change to more arid conditions that resulted in a closed basin. First, it is important to note that all researchers have interpreted that there was an *abrupt* decrease in lake level near the start of the YD. This is illustrated by the small difference in age between the Tintah beach that formed just before water levels dropped near the start of the YD and the age of the oldest organics deposited on the exposed Moorhead subaerial surface in the southern offshore basin only a century or two later (see Bajc et al., 2000; Fisher et al., 2008a). Most have used the age of 12.9 cal (11 ^{14}C) ka BP for this abrupt drop (e.g., Fenton et al., 1983; Broecker et al., 1989; Leverington et al., 2000; Carlson and Clark, 2012), although others have used slightly younger ages (12.8 ka (McMillan and Teller, 2012) and 12.7 ka (Fisher et al., 2008a)). How does a change in hydrological budget occur so quickly, especially if it requires a large climatic change in a proglacial environment? Furthermore, if both the NW and E outlets remained blocked by the LIS, as Fisher et al. (2009) and Lowell et al. (2009) contend, and the S outlet did not carry overflow again until ~10.6 cal (9.4 ^{14}C) ka BP (see Fisher et al., 2008a; Lepper et al., 2011), then the proposed negative hydrological budget would have to have continued for 2300 years, from ~12.9 to 10.6 cal ka BP.

How much water would have to have been evaporated to offset additions to the lake (M + P) and keep it from overflowing? Below is a simple calculation for the hydrological budget of Lake Agassiz during the YD, where M = net meltwater influx, P = precipitation on drainage basin, E = evaporation, OF = overflow from the lake.

$$M + P = OF – E$$

Licciardi et al. (1999) identified 19 cryohydrological basins (CHB) on and adjacent to the LIS and routed meltwater and precipitation from them to the oceans through five pathways in 19 time slices between 21.4 cal ka and today. One of the time slices was 13.0–11.4 cal (11–10 ^{14}C) ka, which roughly coincides with the YD. Changing combinations of the CHBs because of changes in ice divides (based on Dyke and Prest, 1987) and amalgamations and subdivisions of these basins led to reconstructions of flux and routing of meltwater and precipitation through time. LIS ice volumes from Licciardi et al. (1998) were used, and runoff was calculated by subtracting the ice volume in each CHB between two successive reconstructions. Precipitation over each CHB and in each time slice was adjusted for evaporation and transpiration, and calculated using the Community Climate Model of Kutzbach et al. (1998) to modify modern precipitation.

For this paper, I used two approaches based on the Licciardi et al. (1999) modeling to estimate the runoff into Lake Agassiz from meltwater (M) and precipitation (P) during the YD:

(1) Using the value of 0.05 Sv in Licciardi et al. (1999, p. 188) for baseline runoff diverted eastward from Lake Agassiz at the start of the YD, there would have been 1576 km^3 yr^{-1} of overflow from the lake, which was the excess M + P flowing into the lake at that time.

(2) Using tables in Appendix A of Licciardi et al. (1999) and unpublished data, M + P was estimated to range from 3200 to 4100 km^3 yr^{-1} during the 13.0–11.4 ka period.

If an area of 184,000 km^2 is used for Lake Agassiz at the start of the YD (the Tintah beach, Fig. 2A; from Leverington et al., 2000), evaporation (E) in the two approaches above would be:

(1) $E = \dfrac{1576\ \text{km}^3}{184{,}000\ \text{km}^2} - OF = 0.00857$-km-deep layer of inflow annually to Lake Agassiz

(2) $E = \dfrac{3200\ \text{km}^3}{184{,}000\ \text{km}^2} - OF = 0.0174$-km-deep layer of inflow annually to Lake Agassiz.

Thus, to have had a negative hydrological budget in Lake Agassiz, in approach (1), an 8.57-m layer of water must have been lost by evaporation each year to prevent overflow, during an estimated 3–4 month ice-free season, where temperatures were cold (~5°C based on ostracode evidence in Curry [1997], icebergs in Lake Agassiz [Clayton et al., 1965], and modeling by Hostetler et al. [2000]). Using approach (2), 17.4 m of water would have to have been evaporated each year. If the proportion of meltwater (M) to precipitation (P) runoff during the YD was 1 to 5, as indicated in Appendix A of Licciardi et al. (1999), and precipitation dropped to 0 (i.e., total drought), the evaporation needed to offset M would still have to have been very large: 1.7 m/yr and 3.48 m/yr using approaches 1 and 2, respectively.

None of these evaporation rates seem likely in an ice-marginal environment, especially when considering that annual evaporation during a 6-month ice-free season in southern Manitoba today is only 0.65 m/yr (CNC/IHD, 1978) and, as reported in Lensky et al. (2005), evaporation from the hot and dry Dead Sea basin today is only 1.1–1.2 m/yr. Carlson et al. (2009), in response to Lowell et al.'s (2009) negative hydrological budget hypothesis, calculated that 11.9–18.8 m would have to have been evaporated from the basin annually to prevent the lake from overflowing. As reported by Carlson et al. (2009), in a coupled lake-climate simulation of Lake Agassiz by Hostetler et al. (2000), which "is in general agreement with that inferred from paleoecological evidence", the mean annual evaporation rate of the lake was only 0.2 m.

What was the climate like in the region during the Younger Dryas?

In order to help evaluate whether evaporative loss is a tenable hypothesis to explain the low level of Lake Agassiz during the YD, I briefly summarize below several paleoecological and paleoclimatic records from lakes in the Lake Agassiz region that extend back into the YD; their locations are shown in Figure. 1. In this region there are not many paleoecological records that span this time period (see Shuman et al., 2002; Yansa, 2006), partly because the LIS still covered the northern area and partly because early postglacial conditions did not always lend themselves to life in aquatic environments where such evidence is recorded. In fact, in places there are undated sediments, devoid of organic material, that lie below sequences that contain early post-YD dates; this absence of organic material is probably explained by the fact that some of these early post-glacial lakes were cold and turbid (e.g., Curry, 1997; Risberg et al., 1999; Bajc et al., 2000), and vegetation used for dating may not have been established for centuries after the lake formed. However, as described below, there are some dated YD records, and all indicate that the climate was neither unusually warm nor dry during this period.

The idea advanced by Liu et al. (2012) that the presence of gypsum (or proxies for gypsum) in Agassiz sediments at a site in Minnesota dated to the YD indicates aridity in the basin at that time seems unlikely. Even where gypsum is present in the subsurface, and even if it did form during the YD, it may have grown as secondary crystals, just as it is forming today in sediments in the near-surface zone of Lake Agassiz (Young et al., 2000), not as an evaporative mineral on an arid lake

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floor. In fact, modern groundwater in much of the area west of Lake Agassiz is high in Ca and SO_4, and secondary gypsum is common in sediments beyond and within the borders of the lake bed. Saline plants and saline and alkaline soils containing gypsum are present in places today in the Agassiz basin.

Eight examples of lakes containing proxies for YD paleoclimate in the region are given below: 4 from Lake Agassiz itself, 3 from west of Lake Agassiz, and 1 from east of Lake Agassiz (numbers refer to locations in Fig. 1).

1. Offshore Lake Agassiz basin in North Dakota

A detailed paleoecological study of plant macrofossils, insects, and beetles by Fisher et al. (2008a) at several sites on the now-buried subaerial Moorhead surface in the offshore basin of Lake Agassiz west of Grand Forks, North Dakota, controlled by 20 AMS dates, showed that conditions throughout the YD on the exposed floor of the Lake Agassiz basin were "similar to the Rainy River area of northwestern Ontario for this time interval". Many flora and fauna have been identified from these sites, including trees (rooted stumps, wood, bark, bracts, and needles of spruce, pine, fir, tamarack, birch, and aspen), peat, macrofossils and seeds of sedge, rush, herbs, and various emergents and aquatics, insects, and arachnids (mainly beetles) (Fisher et al., 2008a).

The authors state that "after regression of glacial Lake Agassiz during the Moorhead Phase, with lake level lowered below the Southern Outlet sill, a swampy coniferous–deciduous parkland colonized the northern part of the exposed Lake Agassiz basin in North Dakota. Based on the plant and insect fossils identified, we estimate that July temperatures were 1–2°C cooler than at the site today." (Fisher et al., 2008a, p. 1132).

2. Offshore Lake Agassiz basin in northwestern Ontario

About 300 km to the northeast, in the central offshore Lake Agassiz basin of northwestern Ontario, 8 sites were studied that contained abundant organics deposited on the floor of Lake Agassiz exposed during the YD (the Moorhead surface below the level of the Upper Campbell beach). The lake bed during the YD was "wet and poorly drained…supporting a large suite of wetland types" (Bajc et al, 2000, p. 1340). The assemblage of pollen (33 species identified), plant macrofossils (25 species), insects (33 species of caddisflies, 23 families of beetles), and molluscs (23 species) represents "either fluvial or nearshore environments, with a wide spectrum of terrestrial and aquatic habitats" that were brought together by reworking during the transgression of Lake Agassiz over the Moorhead low-water surface (Bajc et al., 2000, p. 1351). These showed that conditions in the region during the YD were "similar to those in the region today" but with "a distinct component [e.g., dwarf shrubs, carabid beetles] whose modern range is much farther north and west of the study region" (Bajc et al., 2000, p. 1352).

3. Lake Manitoba in the offshore basin of Lake Agassiz

Lake Manitoba is a remnant of Lake Agassiz located in the central part of the basin, ~100 km west of Winnipeg. Extensive coring and stratigraphic studies in Lake Manitoba revealed a long postglacial history with substantial changes in lake level and water chemistries during the Holocene (Last and Teller, 1983, 2002). Ostracodes in the sequence were studied by Curry (1997). The hydrochemical history of the past ~11,000 years of a 14.5-m core of the lacustrine sequence, based on ostracodes, indicates that "water in Lake Agassiz was extremely fresh (TDS <100 mg L^{-1}), cold (mean water temperature of about 5°C), and deep (>7 m)" (Curry, 1997, p. 706–707). In marked contrast, the "character of Lake Manitoba changed rapidly during the Holocene" and "the salinity (TDS) of early Lake Manitoba recorded by ostracodes and mineralogy in the overlying post-Lake Agassiz lacustrine sediments was two orders of magnitude greater than that of its late-glacial precursor" (p. 705).

4. Southern margin of Lake Agassiz in North Dakota

In the southern end of the Lake Agassiz basin, a study of plant macrofossils, pollen, insects, and molluscs by Yansa and Ashworth (2005), deposited in shallow-water wetland sediments of Lake Agassiz from 11.9 to 11.3 cal (10.2–9.9 ^{14}C) ka BP, showed little change in paleoclimatic conditions between those recorded during the late stages of the YD in this region and post-YD time, as water rose from the Moorhead low-water stage. "Mean summer temperature may have been about 1–2°C lower than the present day. No change in species composition occurred in the transition from the Younger Dryas to Preboreal" (Yansa and Ashworth, 2005, p. 255). A summary of sites studied in the southern part of the Agassiz basin that contain fossil evidence from the Moorhead low-water phase by Ashworth and Cvancara (1983) also indicates that conditions in the region were relatively cool and moist at this time.

5. Glacial Lake Hind, Manitoba, west of Lake Agassiz

A study of extensive and well dated sediments exposed along the Souris River, ~75 km west of Lake Agassiz (Fig. 1), contains a lacustrine–marshland sequence that spans the YD; AMS dates near the bottom are 11,000 ^{14}C yrs BP (12.9 cal ka) and at the top, below a fluvial sequence, are 9500 ^{14}C yr BP (10.7 cal ka). These sediments were deposited in ice-marginal Lake Hind before ice retreated far enough north to allow it to drain into Lake Agassiz and become a wetland (Sun and Teller, 1997; Boyd, 2003). Plant macrofossils studied by Boyd (2003) and Boyd et al. (2003) in the Lake Hind basin indicate that it remained "wet throughout the YD" until 10.2 cal (9.1 ^{14}C) ka BP. Boyd (2003, p. 147) further states that the "local decline of *Picea glauca* [and replacement by pine] on uplands surrounding the Lake Hind basin is recorded in both pollen and macrofossils, and indicates atmospheric warming up to at least the 17 or 18°C isotherm beginning ~10.1 ^{14}C ka BP. The timing of *Picea* decline at this site is consistent with other records on the Canadian Prairies." Macrofossil studies of new samples in the YD sequence in the Lake Hind basin by Alice Telka (2012, personal commun.) concluded that "the YD was cool to warm and wet; there is no evidence of drought." All aquatics are freshwater types, and "there is no indication of saline or brackish water". There are also charred spruce needles throughout that part of the sequence.

6. Kettle Lake, North Dakota, west of Lake Agassiz

The ~12,000-yr record of Kettle Lake in northwestern North Dakota, 460 km west of Lake Agassiz, provides insight into the drier part of the Agassiz basin. Fifty-three AMS dates in this calcareous silty clay sequence reveal that the record begins about 13.0 cal (11.1 ^{14}C) ka BP, near the start of the YD (Grimm et al., 2011). A *Picea* parkland dominated the sequence until 11.7 cal (10.1 ^{14}C) ka BP. As described by Grimm et al. (2011), endogenic aragonite in the sediment is used as a proxy for drought in the region, and its absence in the sequence before 10.7 cal (9.5 ^{14}C) ka BP (except for a few decades around 12.75 cal ka BP), and the presence of endogenic calcite, are interpreted as indicating the climate during the YD was relatively wet and cool.

7. Deep Lake, Minnesota, east of Lake Agassiz

Isotope and pollen records of a core from Deep Lake in northwestern Minnesota, 45 km east of Lake Agassiz, begin ~12.6 cal (10.6 ^{14}C) ka BP (Hu et al., 1997). An increase in *Picea* during the YD is interpreted as related to a climatic cooling. At the end of the YD, there was a transition from *Picea* parkland to *Pinus* forests, reflecting a change from wetter to drier conditions, and this transition has been found elsewhere in the Midwestern U.S., with dates being time-transgressive from west to east, ranging from ~12 cal ka BP to younger than 10 cal ka BP north of the Canadian border (Wright et al., 2004; see Yansa, 2006). About 100 km to the southeast of Deep Lake, in Steel Lake, the *Picea*–*Pinus* boundary is placed at 11.2 cal ka BP, and this is underlain by sediments with "arboreal macrofossils and clasts containing organic varves" reflecting its deep lake predassor (Wright et al., 2004, p. 613). Interestingly, based only on the δ^{18}O record at Deep Lake, there was a decrease in air temperature and evaporation, as well as an increase in precipitation, after the YD, which Hu et al. (1997) relate to a "lake effect" associated with the expansion of Lake Agassiz from its Moorhead low stage.

It may be worth adding here that other studies to the east in the Upper Midwest also found that the YD was generally wet. A summary in Gonzales and Grimm (2009), centered around a well-dated lacustrine sequence in Illinois, concludes that "the prevalence of *Picea mariana* during the Younger Dryas, together with continued abundance of *Abies*, a reduced but still significantly present *Fraxinus nigra*, and increased *Abies incana*-types, all indicate wet (albeit cooler) conditions during the Younger Dryas Chronozone in northeastern Illinois." This, "together with the absence of boreal post-fire taxa, especially *Betula* and *Pinus*, suggest very wet conditions", as do studies elsewhere in the Great Lakes region (e.g., Jacobson et al., 1987).

8. Moon Lake, North Dakota

Just west of the Lake Agassiz basin, and on about the same latitude as Deep Lake and Steel Lake, is Moon Lake, which has a long record. "*Picea* dominated at Moon Lake from 13,800 [cal] yr BP until 11,600 [cal] yr BP, when *Picea* forest was replaced by a parkland of mixed deciduous forest dominate by *Ulmus* and *Quercus*." (Clark et al., 2001, p. 625) Thus, relatively wet conditions prevailed during the YD, with a shift toward increased aridity after 11.6 cal (10.1 ^{14}C) ka BP across the region (Clark et al., 2002). A synthesis of postglacial spruce records from 20 sites across the Northern Great Plains of North and South Dakota, Montana, Manitoba, and Saskatchewan by Yansa (2006) shows that northward colonization by spruce was part of a spruce parkland encroachment related to warming, but did not reach the Lake Agassiz basin until after the YD; temperatures associated with the arrival of spruce and other plant species indicate that they were "still cooler than present on the Northern Great Plains".

Summary and conclusions

The hydrological history of Lake Agassiz during the YD is important because of the likely role its overflow played in global change. Although the level of this giant lake fluctuated many times during its 5000-yr history, as a result of the interplay between the opening of lower outlets during ice retreat and differential isostatic rebound of the outlet and/or fluctuations in the LIS margin, the Moorhead low-water phase that began near the start of the YD and continued for >1000 yr is distinctive. The routing of overflow from Lake Agassiz during this period is currently being debated, but models show that both eastward and northwestward routes through the Great Lakes–St. Lawrence and Clearwater–Athabasca–Mackenzie systems would have affected oceanic and atmospheric circulation and temperatures. Researchers have presented evidence on the continent and in ocean basins for both of these overflow pathways.

Water budget calculations for Lake Agassiz and paleoecological records for the lake and for smaller lakes in the region provide no support for the hypothesis that the abrupt lowering of Lake Agassiz near the start of the YD, nor the >1000-yr-long low-water level during the Moorhead phase, occurred because of intense drought. Rather, there is support for the long-held conclusion that this decrease in lake level resulted from the opening of an outlet lower than the one at the southern end of the lake. This conclusion should allow researchers to focus on establishing whether the route of overflow from Lake Agassiz was through the Eastern and/or Northwestern Outlets, or along some as-yet-unidentified route. The potential role of freshwater injections into the oceans and their importance in thermohaline circulation and climate during the YD demands a solution to this problem.

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