The Younger Dryas: From whence the fresh water?

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[1] Oxygen isotopic records of meltwater outflow and records of sea level change do not support the idea that fresh waters derived solely from the melting of Northern Hemisphere ice sheets was likely to have stabilized the upper layers of the North Atlantic Ocean and prevented deep convection during the Younger Dryas. Yet there are paleoceanographic indicators that point to a pause in the formation of North Atlantic Deep Water during the Younger Dryas. This apparent conflict in evidence may be resolved by the existence of large, relatively thick, tabular icebergs that spilled out of the Arctic and into the Norwegian-Greenland Sea and North Atlantic. The melting of large icebergs would have no impact on sea level but combined with meltwater runoff would provide enough fresh water to "cap" the North Atlantic. The timing of the start and the end of the Younger Dryas, however, may not have been directly related to freshwater supply.

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1. Introduction

[2] The most detailed record of Younger Dryas cooling in the Northern Hemisphere comes from the ice core records of Greenland. These records indicate that the main cold interval of the Younger Dryas started after 12,900 calendar (cal) years B.P. and stretched from about 12,800 to 11,600 cal years B.P. (Figure 1a). This record has been compared with changes in surface circulation in the North Atlantic [e.g., *Ruddiman and McIntyre*, 1981], with changes in deepwater formation [*Boyle and Keigwin*, 1987; *Keigwin and Jones*, 1989, 1995; *Keigwin et al.*, 1991; *Sarnthein et al.*, 1994] and with the deglaciation history of the North American ice sheets [e.g., *Licciardi et al.*, 1998, 1999; *Clark et al.*, 2001]. The latter authors have linked the Younger Dryas to a proposed maximum in the outflow of melt waters through the Hudson and St. Lawrence rivers that caused the interruption of North Atlantic Deep Water (NADW) formation and led to the return of a very cold climate in the Northern Hemisphere.

[3] The cessation of NADW formation has been explained by a stabilizing of the upper layers of the North Atlantic that prevented convection and deepwater formation. The most commonly proposed means of stabilizing the upper North Atlantic waters has been a flood of relatively fresh waters over the saltier ocean, the "freshwater cap" [*Rooth*, 1982; *Broecker et al.*, 1988, 1989]. This mechanism for the diminution of NADW formation during glacial intervals is an elegant explanation of how natural processes governing climate could "shut off" deep convection in the far North Atlantic during full glacial intervals. It is only natural that this explanation should have been used to explain the temporary return to cold conditions following the end of the last full glacial stage and the cessation of NADW formation in the Younger Dryas [*Broecker et al.*, 1988, 1989].

[4] Certainly, the evidence for NADW being temporarily shut off close to, but not perfectly coincident with, this time is fairly strong [*Boyle and Keigwin*, 1987; *Keigwin and Jones*, 1989, 1995; *Keigwin et al.*, 1991; *Sarnthein et al.*, 1994; *Moore et al.*, 2000]. Such evidence includes indications that the deep waters of the North Atlantic temporarily returned to their glacial character during the Younger Dryas, having geochemical proxies (Cd/Ca ratios and $\delta^{13}C$ measured in tests of benthic foraminifera) indicating relatively "old" bottom waters that were likely derived from high southern latitudes. This lack of relatively "young," locally derived waters in the deep North Atlantic occurred approximately at the same time as a return to an arctic-subarctic planktic fauna in the surface waters of the far North Atlantic and a marked cooling on the surrounding continents. However, it has always seemed counterintuitive that a maximum in Laurentide Ice Sheet melting, feeding a vast amount of water through the Hudson and St. Lawrence rivers into the North Atlantic, should have been coincident with a return to a frigid Northern Hemisphere climate and with the slowest average rate of apparent global sea level rise found between Melt Water Pulses (MWP) 1A and 1B [*Fairbanks*, 1989, 1990; *Bard et al.*, 1990; *Edwards et al.*, 1993; *Peltier*, 2002; *Tarasov and Peltier*, 2005]. The detailed record of sea level rise first provided by *Fairbanks* [1989, 1990] shows two pulses of rapid sea level change that he associated with pulses of meltwater flowing out from ice sheets: MWP 1A, near 13,900 cal years B.P. and MWP 1B near 11,100 cal years B.P. These two pulses occur well before the start of the Younger Dryas and almost 500 years after its end (Figure 1d). Refinement of Fairbanks's Barbados record [*Fairbanks and Peltier*, 2004] bears out the originally proposed relative timing of these meltwater pulses.

[5] The record of sea level rise through the time of the Younger Dryas amounts to about 10 m [*Peltier*, 2002]. If we

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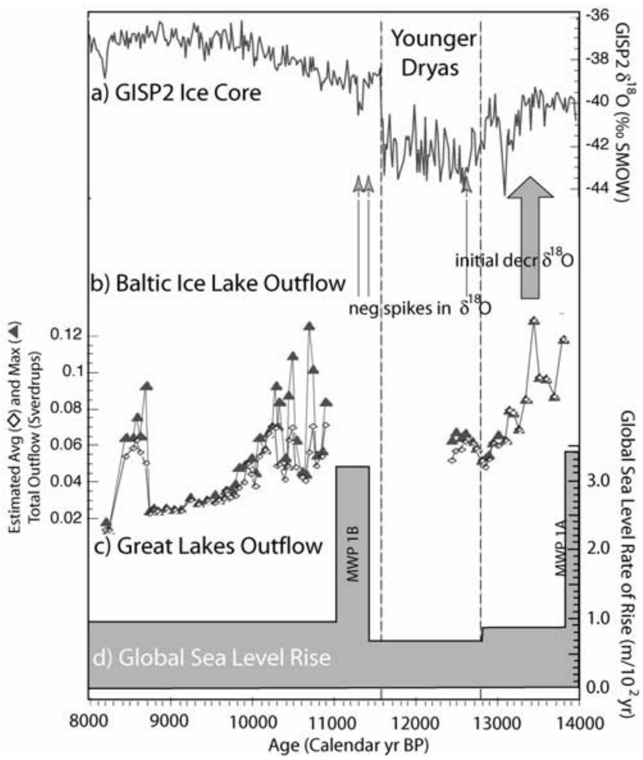

Figure 1. (a) Oxygen isotope data from the Greenland Ice Sheet Project 2 (GISP2) ice core [from *Grootes et al.*, 1993; *Meese et al.*, 1994; *Stuiver et al.*, 1995] compared with (b) the timing of negative oxygen isotopic shift (broad arrow) and negative isotopic spikes in a core record taken near the mouth of the Baltic Sea [*Bodén et al.*, 1997], (c) estimated outflow from the Laurentide Ice Sheet and through the Great Lakes system [*Moore et al.*, 2000], and (d) measured rates of global sea level rise as summarized by *Peltier* [2002].

take the duration of the Younger Dryas as 1200 years (12,800 to 11,600 cal years B.P.) and the volume of water added to the ocean during this interval as 10 m times the ocean surface area in meters (3.62×10^{14} m^2, an estimate that does not account for lowering of sea level during the glacial interval or isostatic adjustments) then the global net average flow rate of fresh waters into the oceans during the Younger Dryas was something less than about 0.10 Sv, about 40% less than the estimated average flow rate solely from the St. Lawrence and Hudson rivers during the Younger Dryas, [*Clark et al.*, 2001]. An average outflow rate of 0.10 Sv of fresh water, if focused solely in the area of NADW formation, might be enough to shut down convection [*Manabe and Stouffer*, 1995, 1997]. However, it seems unreasonable to expect that between MWP 1A and 1B nearly all the meltwaters pouring into the world ocean were dumped in the region of NADW formation. An extensive modeling effort [*Tarasov and Peltier*, 2004, 2005; *Peltier*, 2002], constrained by ice sheet margins [*Dyke*, 2004], relative sea level change and crustal response to loading and unloading, suggests that there may have been a substantial out flow of meltwaters and ice into the Arctic Ocean from the Keewatin Dome of the Laurentide Ice Sheet. These authors suggest that peak outflow may have coincided with the initiation of the Younger Dryas [*Tarasov and Peltier*, 2005] and that over the 300 year peak discharge interval flow reached rates of 0.1 to 0.14 sverdrups (Sv) (10^6 m^3/s). *Tarasov and Peltier* [2005] and *Fairbanks and Peltier* [2004] argue that injection of fresh water into the Arctic, which feeds directly into the regions of the NADW formation is a much more effective way to stabilize the high North Atlantic than supplying this water at much lower latitudes and then transporting it into the region of NADW formation. In today's ocean, convection in the Norwegian-Greenland Sea and overflow into the North Atlantic appear to be more critical areas [*Aagaard and Carmack*, 1994].

[6] Although both the sophistication of this model and its results are impressive, oxygen isotope data from cores taken from the Mendeleyev Ridge [*Poore et al.*, 1999], in the Eurasian Basin of the Arctic Ocean and in the Norwegian-Greenland Sea [*Stein et al.*, 1994] show mainly MWP 1A and 1B, not the massive flux at ~12,800 cal years B.P. proposed by *Tarasov and Peltier* [2005]. There is a small negative perturbation in oxygen isotope records near this time in some of the cores taken near the Fram Strait [*Nørgaard-Pedersen et al.*, 2003]. Given the difficulty of radio carbon dating material from the Arctic Ocean, these apparent disagreements with the model may be resolved in the future. Perhaps a more worrying aspect of the *Tarasov and Peltier* [2005] model is that their average rate of sea level rise over the Younger Dryas interval is nearly all explained by the North American contribution to that rise. Given the existence of the Scandinavian Ice Sheet during this interval, as well as the Southern Hemisphere ice sheets (which apparently did not experience a Younger Dryas cool interval), ascribing 10 m of sea level rise solely from North America seems excessive.

[7] A tightly constrained history of Laurentide meltwater flow from the southern margin of the Laurentide Ice Sheet was based on the stratigraphy of sediments in the lower Great Lakes, changes in lake levels, and the oxygen isotope record of meltwaters in the lakes [*Moore et al.*, 2000]. A linked box model based on these data was used to calculate water flow through the Great Lakes drainage system. It indicated the maximum flow through the system that drained much of the southern margin of the Laurentide Ice Sheet occurred when lake levels were at their lowest. These maximum flow rates were nearly coincident with MWP 1B and MWP 1A (Figure 1c). Thus there is evidence both from the Arctic Ocean on the north side of the Northern Hemisphere ice sheets and from the Great Lakes at the southern margin of the Laurentide Ice Sheet that during the relatively warm Bölling/Alleröd and during the warm interval following the Younger Dryas the ice sheets were melting, were providing meltwaters to the surrounding region and were causing relatively rapid sea level rise. Times of maximum meltwater flow from the Laurentide Ice Sheet and rapid rises in sea level that result from melting of land-based ice sheets both indicate that peaks in the flow of waters from melting ice sheets into the ocean occur during warmer intervals that precede and follow the Younger Dryas event by several hundred years. They do not coincide with it and therefore could not have caused it.

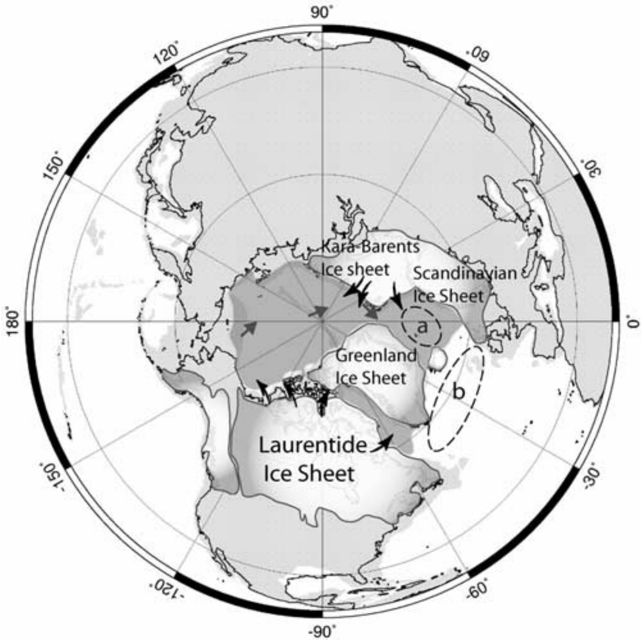

Figure 2. Approximate location of the major continental ice sheets at the end of the last glacial stage. Areas of proposed sea ice extent are shaded in medium gray. Three broad gray arrows in the Arctic Ocean indicate location and direction of iceberg movement indicated by ice scour scars on plateaus and ridges (see text for description). The easternmost arrow is located on the Yermak Plateau, just north of the Fram Strait connecting the Arctic Ocean with the Norwegian-Greenland Sea. Thin black arrows indicate location of troughs and deep valleys that likely fed ice streams from the ice sheets into the Arctic Ocean seas. Areas "a" and "b" indicate regions of deep oceanic convection in the Norwegian-Greenland Sea and North Atlantic Ocean, respectively [from *Aagaard and Carmack*, 1994]. Modern continental outlines are shown in black with continental crust shaded in light gray (base map from Ocean Drilling Stratigraphic Network website: www.odsn.de).

[8] The problem with this second model of meltwater outflow is that it does not directly provide the dramatic surge of outflow and capping of the North Atlantic that everyone expected and hoped for. The timing is wrong, based both on isotopic evidence for meltwater flux [*Moore et al.*, 2000; *Poore et al.*, 1999; *Stein et al.*, 1994] and on apparent rates of sea level rise [*Fairbanks*, 1989, 1990; *Bard et al.*, 1990; *Edwards et al.*, 1993]. Meltwater outflow from the Scandinavian Ice Sheet would have been more proximal to the areas of convection and NADW formation, but oxygen isotope evidence from the Baltic Ice Lake outflow [*Bodén et al.*, 1997] suggests a modest shift to more negative isotopic values near 13,300 cal years B.P., with negative spikes in isotopic values during and after the Younger Dryas (Figure 1b). Again, the timing seems wrong.

[9] In spite of the elegance of the meltwater cap model, it appears that a sudden spilling of meltwater from the southern margins of the Northern Hemisphere ice sheets flowing over land and into the North Atlantic could not have provided the cap for North Atlantic convection by itself. The prevention of deep convection in the North Atlantic by freshwater stabilization of the upper ocean appears to be a very workable mechanism; but if the North Atlantic was thus capped, from whence did the fresh water come? The careful modeling done by *Tarasov and Peltier* [2005] may provide the answer; however, the evidence for large amounts of liquid fresh water in the Arctic at the onset of the Younger Dryas is weak at present. Whatever the source, it does not appear to have caused a major jump in sea level. Yet the only large volume of fresh waters available to cap the North Atlantic at 12,800 cal years B.P. had to be associated with the Northern Hemisphere (Figure 2), but did it have to be land-based?

2. Was There a Source of Thick Floating Ice?

[10] As suggested by *Tarasov and Peltier* [2005], perhaps we should look toward the northern, rather than the southern, margins of the Northern Hemisphere ice sheets for the source of the fresh waters. Ice shelves of 1 km thickness have been proposed for the glacial Arctic Ocean [*Mercer*, 1970; *Hughes et al.*, 1977; *Grosswald and Hughes*, 1999]; however, others believe that Arctic ice cover during glacial intervals was much as it is in interglacial times [*Clark*, 1990; *Ishman et al.*, 1996; *Bischof and Darby*, 1997; *Philips and Grantz*, 2001]. *Vogt et al.* [1994] were the first to present evidence that calving marine ice shelves in the Arctic produced deep-draft icebergs that were 500 to 700 m thick. These icebergs resulted in a grounded ice ridge on the Yermak Plateau 400 to 600 m thick, with signs of erosion down to 850 m. Evidence of ice scour, striations, flutes and other signs of erosion (as well as aprons of redeposited sediments) have been found to depths of 500 m on the Chukchi borderland and Northwind Ridge and to depths of 950 m or more on the Lomonosov Ridge [*Polyak et al.*, 2001; *Kristoffersen et al.*, 2004]. Over the Chukchi plateau and Northwind Ridge erosional scarring indicate that the transport of deep-draft icebergs was to the northwest [*Polyak et al.*, 2001]. On the Lomonosov Ridge, erosional features and redeposited sediments indicate transport was to the east and southeast, while on the Yermak plateau, transport was to the south [*Kristoffersen et al.*, 2004] (three broad gray arrows in the Arctic Basin in Figure 2).

[11] *Polyak et al.* [2001] used this evidence of erosion to support the possibility of thick ice shelves covering much of the Arctic during glacial intervals. *Kristoffersen et al.* [2004] take a more middle ground. They believe that there were more restricted ice shelves during glacial intervals that fed large tabular icebergs into the Arctic seas and that these deep-draft icebergs accounted for much of the erosion seen on shallow plateaus within the Arctic basin. Whether you hypothesize extensive ice shelves extending into the Arctic basin or more restricted ice shelves that fed thick, tabular icebergs into the basin, these observations lend credence to the proposal that the ice cover in the Arctic was quite thick during glacial intervals. On the present day continental shelves of the Arctic Ocean there are numerous, deep, broad valleys that likely carried ice streams and could have fed these Arctic Ocean ice shelves from the northern edges of the continental ice sheets (Figure 2, thin black arrows). On

the Eurasian side of the Arctic these valleys (or troughs) stretch from Svalbard to the Taimyr Peninsula, with the St. Anna Trough and the Voronin Trough being the most prominent in the Barents and Kara seas. On the North American side of the Arctic Ocean, the continental shelf between the northeastern coast of Greenland to Cape Bathurst in northwestern Canada is more narrow and may not have been ice covered at the end of the last glaciation [*Dyke*, 2004], but numerous deep valleys cut between the Queen Elizabeth Islands and across the shelf of Greenland. In northwestern Canada the two most prominent troughs lie in the Amundson Gulf and the McClure Strait and may have fed ice into the Arctic from the Keewatin Dome.

[12] Along the northern margin of the North American continent the Laurentide, Innuition, and Greenland ice sheets, or ice streams from these ice sheets, likely extended across relatively narrow shelves into the Arctic basin as the most recent glacial phase approached its end. On the Eurasian margin there was an extensive ice sheet on the shelves of what are now the Barents and Kara seas. The Barents-Kara Ice Sheet is likely to have extended from the Taimyr Peninsula on the east, thickening to the west as it merged with the Scandinavian Ice Sheet. It was relatively large about 90 ka [*Svendsen et al.*, 2004] and actually diminished in size through the last glacial interval as the Scandinavian Ice Sheet grew. At the last glacial maximum it did not extend far into the Siberian continent [*Polyak et al.*, 2002], but it is believed to have been from 200 to 1400 thick over much of the Barents-Kara shelf area [*Svendsen et al.*, 2004].

[13] In addition to the Arctic Basin itself, ice streams from the Laurentide, Innuition and Greenland ice sheets fed into the Labrador Sea and the Greenland and Scandinavian ice sheets fed into the Norwegian-Greenland Sea. Much of the shelves surrounding these seas lie at or below 200 m and could have been covered by extensive, thick ice shelves. This thick ice from the Arctic seas might well have been the source of the ‘‘missing’’ fresh water needed to cap North Atlantic convection in the Younger Dryas. The apparent collapse of the Keewatin Dome of the Laurentide Ice Sheet near the start of the Younger Dryas as proposed by *Tarasov and Peltier* [2005] could have provided a substantial amount of ice to the Arctic. If in fact the collapse of the Keewatin Dome occurred slightly earlier than they propose (i.e., just following MWP-1A) it would have had no effect on sea level during Younger Dryas time.

3. Did the Thick Ice Occur at the Right Time?

[14] Although there is good evidence of very thick ice eroding the tops of most of the relatively shallow regions of the deep Arctic basin, determining the age of the erosion that caused a hiatus in a stratigraphic record can be difficult. Trying to determine the exact age of extensive erosional features seen on Arctic shelves, plateaus and ridges is particularly challenging when few biostratigraphic markers are preserved. Dating of the erosional features on the Yermak plateau from samples in ODP Site 910 indicates that the erosion took place about 660 ka (just prior to or during MIS 16) [*Flower*, 1997]. On the Lomonosov Ridge the stratigraphy in a piston core taken at over 1 km water depth and studied by *Jakobsson et al.* [2001] indicate erosion having taken place during MIS 6. At 400 m below present day sea level a piston core from the Chukchi rise gives evidence of over compacted sediment deposited before 13 kyr [*Polyak et al.*, 2001]. Thus it appears that these erosional events took place during major glaciations. Very thick ice may not have been common during every glacial interval; however, this does not exclude the presence of relatively large tabular icebergs during all glacial intervals in the Arctic. It only indicates that very thick icebergs with drafts approaching 1 km may not be a common feature of the Arctic during the Pleistocene, but they do occur repeatedly. To better establish the pervasiveness of deep draft icebergs in the Arctic, the tops of other shallow ridges and plateaus should be imaged and sampled (e.g., the Morris Jessup Ridge, the southwestern end of the Lomonosov Ridge). To more thoroughly explore the possibility of deep draft icebergs invading the Norwegian-Greenland Sea, a more complete exploration of the ridges and plateaus in this region should be undertaken (e.g., the shoaling eastern part of the Vorring Plateau and the Hovgaard Ridge).

[15] The evidence for thick tabular icebergs in the Arctic Ocean during the Younger Dryas is sketchy at best. Most of the Arctic cores that have been studied in detail show a low average accumulation rate during the Younger Dryas time, although this does not hold for every core with radiocarbon dates that bracket the Younger Dryas [*Poore et al.*, 1999; *Darby et al.*, 1997]. Low accumulation rates are commonly associated with low basal melting rates of Arctic ice [*Clark et al.*, 1980, 1986; *Stein et al.*, 1994; *Darby et al.*, 1997]. In their study of piston cores along the continental margin northeast of Svalbard, *Knies et al.* [1999] indicated a minor peak in ice-rafted debris and the absence of planktonic foraminifera in a $\sim$50 cm interval above glacial transition I (<12.6 ka ^{14}C). Lower sediment accumulation rates in the Arctic during the Younger Dryas, along with low carbonate accumulation and few benthic foraminifera [*Stein et al.*, 1994], would be consistent with extensive ice cover and little seasonal melting of ice.

[16] *Darby et al.* [2002] present a detailed study on the timing of outflow from various source areas in the Arctic basin. In their study of ice-rafted debris (IRD) in a box core (PS1230) from the central Fram Strait they identified both the IRD source and the timing of influx as it entered the Norwegian-Greenland Sea. They relate the youngest peak in the delivery of ice-rafted debris (AL1) to the Heinrich event H-O (the Younger Dryas) and the older peaks in IRD to older Heinrich events [*Bond et al.*, 1999]. However, they note that their IRD peaks all appear to be $\sim$1.5 kyr older than the Heinrich events.

[17] This problem in correlation is as yet unresolved, and an earlier paper [*Dowdeswell et al.*, 1999] that looked at nine cores scattered throughout the Norwegian-Greenland Sea could find no consistent relationship between IRD accumulation among the cores or between these cores and the Heinrich events of the North Atlantic. Other studies in the region [*Bauch et al.*, 2001; *Nørgaard-Pedersen et al.*, 2003] note a higher concentration of IRD during the Younger Dryas only in the southern reaches of the Norwe-

gian-Greenland Sea. In the Fram Strait region, the abundance of planktonic foraminifera is generally low at this time. The lack of a tight correlation between IRD influx in the Norwegian-Greenland Sea and the timing of the Younger Dryas in these cores may also have to do with the strong overprint of IRD derived from the western part of the Scandinavian Ice Sheet and the eastern part of the Greenland Ice Sheet. Perhaps a more fundamental concern is whether we can assume that the accumulation rate of IRD at a particular location has a direct linear relationship to the volume of ice passing over that location. Does the debris load per unit volume of ice in a large tabular iceberg equate to that of the icebergs calving from smaller ice streams entering into the Norwegian-Greenland Sea?

4. Could There Have Been Enough Volume of Ice?

[18] If we sum the area of the Arctic basin (4.74×10^{12} m^2) [*Jakobsson*, 2002] plus the area of those parts of the North American Arctic shelf (0.18×10^{12} m^2) and the Eurasian shelf (2.06×10^{12} m^2) likely to have been covered by ice, we have a total area of 6.98×10^{12} m^2 that could have been covered by relatively thick ice at the end of the last glacial maximum (LGM). We might add to these areas that of the Labrador Sea (Baffin Bay plus Davis Strait, 1.24×10^{12} m^2) [*Jakobsson*, 2002]. This area was not in direct communication with the Arctic, but received ice from the Laurentide, Greenland and Innuition ice sheets and flowed into the North Atlantic. The Norwegian-Greenland Sea (Greenland Sea plus Iceland Sea plus Norwegian Sea, 2.61×10^{12} m^2) [*Jakobsson*, 2002] received ice streams from the Greenland and Scandinavian ice sheets, and this flow of ice must to some extent have blocked free exchange with the Arctic basin during the LGM.

[19] This gives us a total potential area of Arctic ice of 10.83×10^{12} m^2. As sea level began to rise from the end of the LGM to the start of the Younger Dryas (some 50–60 m), ice grounded below sea level on shelves and in ice streams would have been lifted and flowed more freely into the deeper basins. However, how much ice was there in the Arctic seas to feed (solid) fresh water into North Atlantic? In an attempt to see how much might have been supplied, let us assume that the ice cover in the deep Arctic basin was 90%, and because there is no evidence for really thick, tabular ice during the most recent glacial maximum, assume that the average thickness of the ice was no more than 400 m. On the deep Arctic shelves we assume that on average the ice was thinner, say, 200 m. If we allow the ice in the Arctic basin and shelves (as assumed above) to flow into the Norwegian-Greenland Sea, the average flow over 1200 years of Younger Dryas time would be 0.06 Sv. If *Tarasov and Peltier* [2005] are correct (or nearly so) in their proposed timing of outflow from the Keewatin Dome into the Arctic, this surge could have provided the impetus for a relatively rapid flow of ice and water through the Fram Strait and into the regions critical to NADW formation.

[20] This estimate does not take into account ice floating in the Norwegian-Greenland Sea and Labrador Sea that derived directly from the Scandinavian, Greenland, Innuition, and Laurentide ice sheets. If these seas were about 70% covered with ice averaging 300 m thick, they would have supplied another 0.02 Sv during the 1200 years of Younger Dryas time. We should also take into account the generally low salinity of the Arctic waters that result from high runoff and low evaporation and the enhancement of that low salinity by winter freezing and salt exclusion. The creation of fresh waters by freezing of seawater would have had no effect on sea level. All of these factors would have contributed to very low-salinity waters being supplied to the North Atlantic from the Arctic seas.

[21] Although this ice was active, flowing into, around, through, and out of the Arctic seas, it was also being renewed by ice flowing out from the ice sheets. Sea level was only affected by this "new" ice replacing that already floating at the start of the Younger Dryas. The floating ice volume at the start of the Younger Dryas had no effect on sea level as it melted. From the assumptions made above, we estimate that such melting, averaged over the duration of the Younger Dryas, could have provided about 0.08 Sv of fresh water.

[22] With this estimate of fresh water supplied by the melting of floating ice, it would require 20% of the total measured sea level rise (i.e., 0.02 Sv) to be derived from grounded ice and meltwaters flowing into the Arctic and adjacent seas to provide the critical >0.1 Sv required to prevent deep convection in the high-latitude North Atlantic [*Manabe and Stouffer*, 1995, 1997]. Although much of the Younger Dryas record is missing from the Great Lakes model of outflow (because of poor carbonate preservation, Figure 1c), a reasonable estimate of "background" flow during this interval would be about 0.06 Sv, more than enough to meet the critical level of freshwater supply when combined with our estimates of fresh water derived from floating ice.

5. Was the Younger Dryas a Unique Event?

[23] If the melting of ice sheets and the outflow of ice bergs from the Arctic seas typically caused a reversal in climate during deglaciations, we would expect such features to be common in the marine Pleistocene record. Although there have been only a few detailed studies of deglaciations in marine cores [e.g., *Oppo et al.*, 1998, 2001; *McManus et al.*, 2003], there have been no clear-cut examples of a climatic event exactly like the Younger Dryas in timing, duration and magnitude. For both the MIS 5/6 and MIS 11/12 transitions there are perturbations on the over all warming trend associated with deglaciation. On the transition from MIS 6 to MIS 5 there appears to have been a short reversal in the warming trend associated with oxygen isotopes and other indicators of a cooler interval [*Oppo et al.*, 2001]; whereas on the transition from MIS 12 to MIS 11, there appears to have been a somewhat longer pause or plateau in the warming trend [*Oppo et al.*, 1998; *McManus et al.*, 2003]. The main thrust of the papers cited above does not focus on these specific events, but rather looks at them as part of the overall millennial-scale variability of Pleistocene climate [*Bond et al.*, 1999]. These perturbations on glacial-interglacial transitions are seen as being related to a natural variability in climate that is amplified by coupled surface-deepwater oscillations [*Oppo et al.*, 2001]. Thus the

Younger Dryas might be viewed as an amplified response to a natural climate cycle. If this is true, the exact character of such perturbations results from both the phasing of the millennial-scale cycle with respect to the Milankovitch cycles and to random variability in the response to such climatic forcing and amplification. However, the exact nature of the millennial-scale climate forcing is still a matter of debate.

[24] If we think of the Younger Dryas as a phenomenon driven solely by the rate of freshwater supply to the region critical to the formation of NADW, then the records shown in Figure 1 lead us to wonder why the Younger Dryas did not start at least 14,000 years ago and last until 10,500 cal years B.P. There certainly seems to have been enough fresh water and ice being delivered to the North Atlantic to do the job. However, if we think the Younger Dryas and similar such events at other glacial stage terminations were driven by climate variations, then perhaps we should ask not whether there was enough fresh water to stop convection, but rather was there enough salt water to start it [*Broecker et al.*, 1990]? *Broecker et al.*'s [1990] concept followed the *Fairbanks* [1989, 1990] papers that first showed the timing of the major pulses in melt water were different from the timing of the start and end of the Younger Dryas. All that is needed is the mechanism of delivering the salt. The Gulf Stream waters supply the salt to the Norwegian-Greenland Sea that is critical to the convection in that region and in turn these waters overflow into the North Atlantic Basin and play a role in the further mixing and convection that leads to the formation of NADW [*Aagaard and Carmack*, 1994]. Without this salt supplied from lower latitudes, relatively brackish waters would dominate surface waters of the region and convection would be minimal. There is evidence of subsurface flow of more saline Atlantic waters into the Norwegian-Greenland Sea [*Bauch et al.*, 2001; *Nørgaard-Pedersen et al.*, 2003] even during the glacial maximum, and although convection did probably take place in polynyas along the eastern side of the Norwegian Greenland Sea, it may have been intermittent during the Younger Dryas [*Bauch et al.*, 2001].

[25] Thus it could be that the timing of the Younger Dryas was more closely tied to climate-induced shifts in the Gulf Stream and the implementation of the salt oscillator mechanism [*Broecker et al.*, 1990] than to the adequacy of freshwater supply to stabilize the water column. If the presence of saltier waters in the regions of convection is the critical element in the turning on and off of NADW formation then what we must strive for is a careful evaluation of the position of the Gulf Stream going into and out of the Younger Dryas cold interval. Did the southward movement of the Gulf Stream coincide with, or slightly precede the Younger Dryas start? Did its return northward cause the end of the Younger Dryas? Only a very careful look at the relative phasing of shallow water and deepwater proxies in high-resolution cores can answer this question. The work of *Ruddiman and McIntyre* [1981, and references therein] have shown that such swings in the Gulf Stream did take place at approximately the right times, but the phasing of these swings relative to other paleoceanographic and paleoclimatic changes has yet to be revealed.

[26] We may not now adequately understand the mechanism(s) that drive millennial-scale variability in climate or even the details of the surface-deepwater oscillations that amplify it. However, we can strive to understand better the mechanisms that controlled the nature of the Younger Dryas perturbation. We know that it occurred after the first phase of rapid meltwater discharge into the oceans (MWP 1A); and if the unspecified main driver of cool-warm oscillations initiated the return to a cooler climate, then how was it amplified? Toward the end of MWP 1A sea level had risen about 50 m to 60 m and had started to reflood continental shelves and partially lift grounded ice shelves from the sea floor. This may have enhanced faster flow of ice into the high-latitude oceans (particularly from the Keewatin Dome) [*Tarasov and Peltier*, 2005], but the return to a cooler climate reduced melting (as evidenced by the generally lower accumulation rates in most Arctic cores noted above, by a lower rate of sea level rise, and by reduced outflow from the Great Lakes, Figure 1). The response to this first rapid rise in sea level may not have been instantaneous. In this way floating ice may have been gradually built up and stored in the high-latitude seas. The image of an ocean filled with large tabular icebergs, all trying to exit the Fram Strait and enter a Norwegian-Greenland Sea, also crowded with ice as sea level rose, causes one to wonder also about the possibility of an ice jam in that relatively narrow ($\sim$1500 km) passage. Such an occurrence, if possible at all, would probably be highly variable in character from one deglaciation to the next. The timing of the initial outflow from the Baltic Ice Lake (13,400–13,100 cal years B.P., Figure 1b) [*Bodén et al.*, 1997] may mark the initial clearing of the southern Norwegian-Greenland Sea of ice and the first stage leading to a large supply of floating and melting ice into the region critical to the formation of NADW.

[27] Once the ice and meltwaters entered the Norwegian-Greenland Sea and the North Atlantic, amplification of the cooling trend could have had its full effect in the shutting down of deep convection. The estimated average outflow of floating ice provided here is nearly enough to shut down North Atlantic convection; however, it is probably only through the combined effect of meltwater from the continental ice sheets and floating ice, as well as low-salinity surface water transported southward from the high-latitude seas that sufficient fresh water could be delivered to cap the North Atlantic.

6. Conclusion

[28] The freshwater capping of the North Atlantic convection that would cause the temporary cessation of NADW formation and the temporary return to near glacial climates of the Younger Dryas is an attractive hypothesis with some evidence to support it. However, neither the record of sea level rise nor the record of Great Lakes meltwater flux match the timing of the start and end of the Younger Dryas. Thus if we are to hold to this hypothesis, we need a source of fresh water sufficient to cap the North Atlantic without raising sea level by the amount that would be necessary if that fresh water came solely from surging ice streams and melting ice sheets on land in the Northern Hemisphere.

Recent modeling of the melting of the Laurentide Ice Sheet lends support to the idea that the Arctic is the source for this fresh water; however, the rate of sea level rise seems to suggest that much of this Arctic supply may have been in the form of floating ice. Large tabular icebergs sourced from the Arctic seas are both likely to have been present and proximal to the most important regions of North Atlantic convection. The volume of fresh water from such a source appears to be adequate in combination with freshwater runoff, but ideas about the timing and exact source and path of delivery remain open to question, requiring further investigation. The flux of IRD may be an inadequate proxy in this search.

[29] The timing of the start and end of the Younger Dryas, however, may have nothing to do with freshwater supply rates, but rather be dependent on natural, millennial-scale climatic variations that control the path of the Gulf Stream. Thus an adequate supply of fresh waters in the regions critical to the formation of NADW may be a necessary part of the Younger Dryas story, but it is not sufficient without shifts in the Gulf Stream driven primarily by millennial-scale variability in climate.

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