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Strong deep-water formation in Baffin Bay ensured the heavy snowfall that initiated the Last Ice Age in the Northern Hemisphere

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Abstract

The extremely heavy precipitation that initiated the Last Ice Age (the Wisconsin Glaciation in Canada) was caused by a strong and persistent atmospheric low-pressure system centered over the northern Labrador Sea and southern Baffin Bay. This system, called the Labrador Low, was dependent on strong deep-water formation in the northern end of Baffin Bay. The replacement for the sinking deep water consisted of warmer and more saline Irminger Current water that mixed into the northward-flowing West Greenland Current near the center of the Labrador Low. The heavy precipitation in northeastern Canada began after the stratification in Baffin Bay was eliminated by the southward flow of denser Atlantic water through the Nares Strait. This temporary flow began when the oscillating Atlantic Meridional Oceanic Circulation (AMOC) flow reached a maximum greater than today. This sent Atlantic water westward, north of Greenland and through the Nares Strait. Although the extremely heavy snowfall began the Wisconsin Glaciation in Canada, the initiation of the Last Ice Age in Eurasia was a more complex process and was delayed by about 4,000 years by formation of the Hudson Strait ice dam.

Keywords: Deep-water formation, Last Ice Age, initiation, Barbados surveys, rapid climate change**.**

1. Method.

This paper discusses differences from today in northern North Atlantic Ocean currents derived from the Gulf Stream. These differences enabled strong deep-water formation in Baffin Bay, and initiated the Last Ice Age. The modern pattern of currents is similar to the Last Interglacial and is displayed in Figure 1. The history of oceanic circulation variations and resulting climate changes during the Last Interglacial-Glacial climate transition is derived from foraminiferal species abundance variations in deep-sea cores[1], tree pollen records in German lake sediment[2], and paleo sea level changes on the now uplifted island of Barbados[3]. The tree pollen record provides a time scale for the changes and for the severity of the climate change in Europe. The beginning age of the interval of Baffin Bay deep-water formation during the transition is found from the first dated sea level fall caused by onset of new glaciation in Canada [4]. The ending age is found from a European tree pollen record[2] and the thorium-uranium age of a Barbados coral specimen[3].

2. Introduction.

Without a change in oceanic circulation and precipitation, detailed numerical modeling has shown that cooling caused by a reduction of summer insolation due to the Milankovitch orbital effect would not have been able to initiate new ice sheet growth in northeastern Canada even with an initial layer of glacial ice[5]. In an alternative proposal, a quite large increase of snowfall in northeastern Canada started the Last Ice Age[6]. The high level of annual precipitation was proposed to have been caused by a persistent atmospheric low-pressure system. This system was generated by warmer surface water at the south end of Baffin Bay and the northern part of the Labrador Sea[1] and the contrasting low temperatures of the adjacent lands[Fig. 2]. The warmer water was a result of the onset of strong deep-water formation at the north end of Baffin Bay. This result would only have been made possible by the prevention of the near-surface stratification in Baffin Bay, which today makes the formation of winter sea ice possible and keeps the sea west of Greenland cold. This stratification had been caused by the inflow of polar water of lower salinity and density through the Nares Strait. The prevention of the polar water inflow was a necessary but not a sufficient condition for the warmth of open water west of Greenland. The additional requirement is a sea surface salinity and warmth like that of today in the Irminger Current of the Northern Gyre and a warmer West Greenland Current at its point of origin. This higher salinity of the West Greenland Current at the

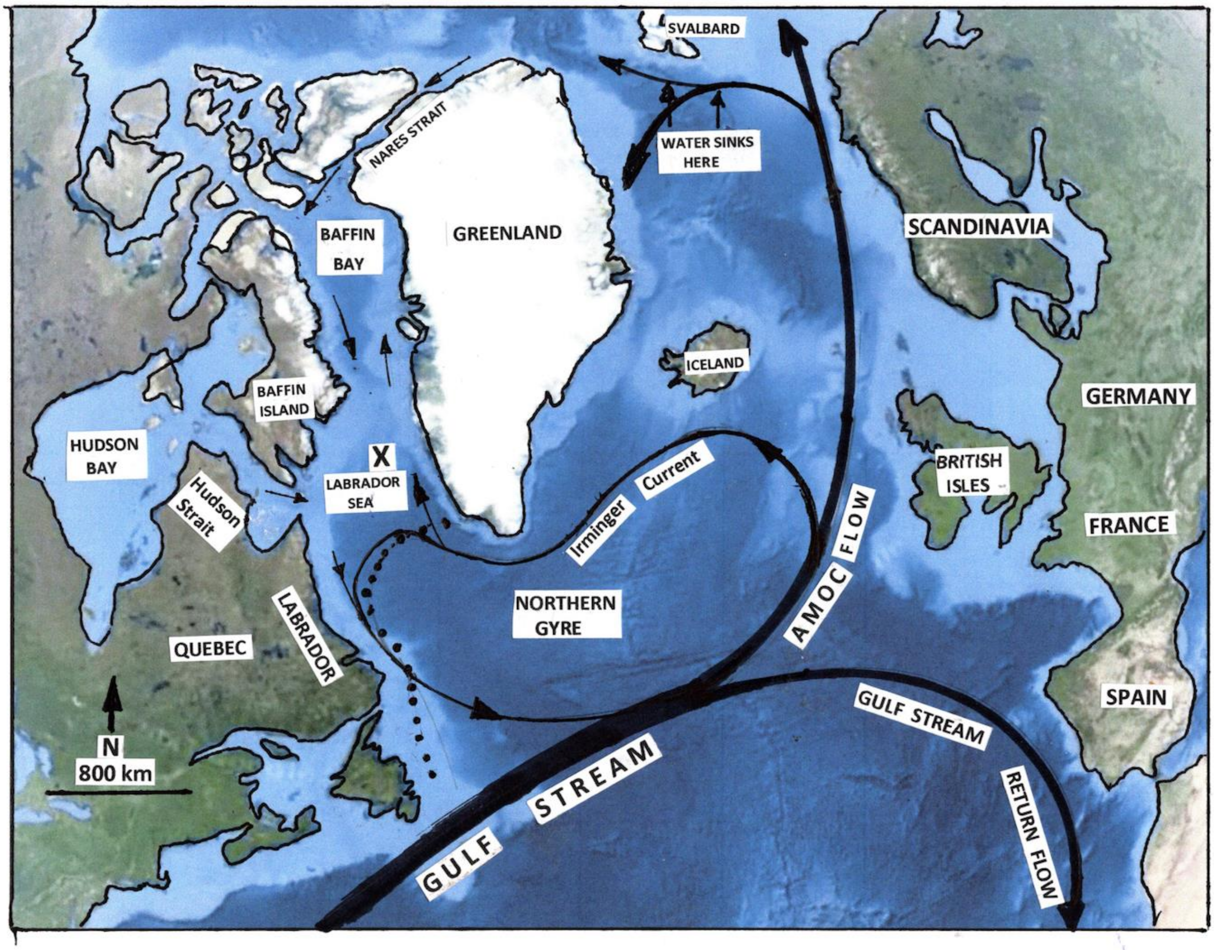

Figure 1. Gulf Stream Currents today and in the Last Interglacial in the northern North Atlantic and the region west of Greenland. Baffin Bay, Hudson Bay, and the northern and western parts of the Labrador Sea are seasonally covered with sea ice. Dotted line is sea ice limit. X is the site of deep-sea sediment core HU75-58 in which R.H. Fillon found evidence for relatively warm sea surface conditions as the Last ice Age began[1]. This and subsequent maps were derived from Google Earth images. Sinking deep water reaches intermediate depths and flows toward the south.

beginning of the Last Ice Age enabled strong deep-water formation at the north end of Baffin Bay and unusual warmth at the south end. This oceanic warmth generated the Labrador Low pressure system of Figure 2, which brought extremely heavy snowfall to the surrounding region, thus initiating the Last Ice Age.

3.The process of initiating the Last Ice Age by first eliminating the stratification in Baffin Bay.

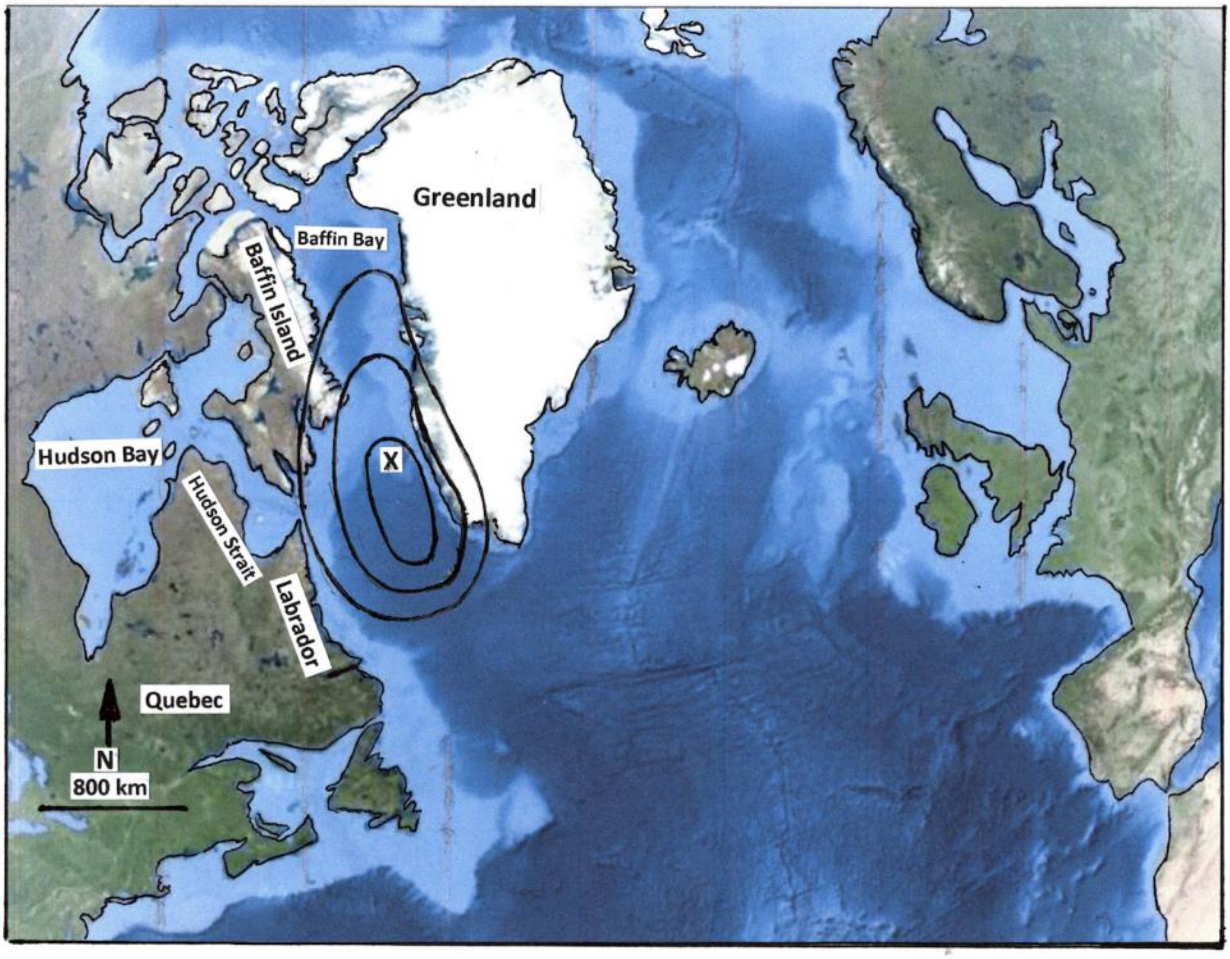

Figure 2. Hypothetical isobars caused by temperature contrast between relatively warmer subpolar sea west of Greenland and surrounding cold lands. This warmth resulted from deep water formation in the northern end of Baffin Bay. This dominant low-pressure system caused the extremely heavy snowfall that initiated the Wisconsin Ice Age in North America at 120 ka BP. X is the location where warmer subpolar species of foraminifera were found in deep-sea sediments. The initiation of the last Ice Age in Eurasia was a more complex process, see text.

3.1 Denser Atlantic water entered Baffin Bay through the Nares Strait.

Atlantic water flow through the Nares Strait began at the end of a series of climate factor changes[6]. At the end of the Last Interglacial climate interval, summer was nearing the maximum distance from the sun and from the perihelion point in Earth's elliptical orbit. Consequently, the summer solar radiation on northern Africa was nearing a minimum, thus causing a lower level of precipitation during the West African monsoon season and a low volume rate of the Nile River flow. Consequently, the salinity of the Mediterranean Sea and its outflow rate at Gibraltar were approaching maxima that were greater than today. Because some of the saline outflow diffuses into the AMOC flow[7], the result was a stronger flow of the AMOC than today. Some of this denser Atlantic water flow was diverted to the west along the north coast of Greenland. When it entered the Nares Strait, it would have replaced the flow of fresher and less dense polar ocean water that

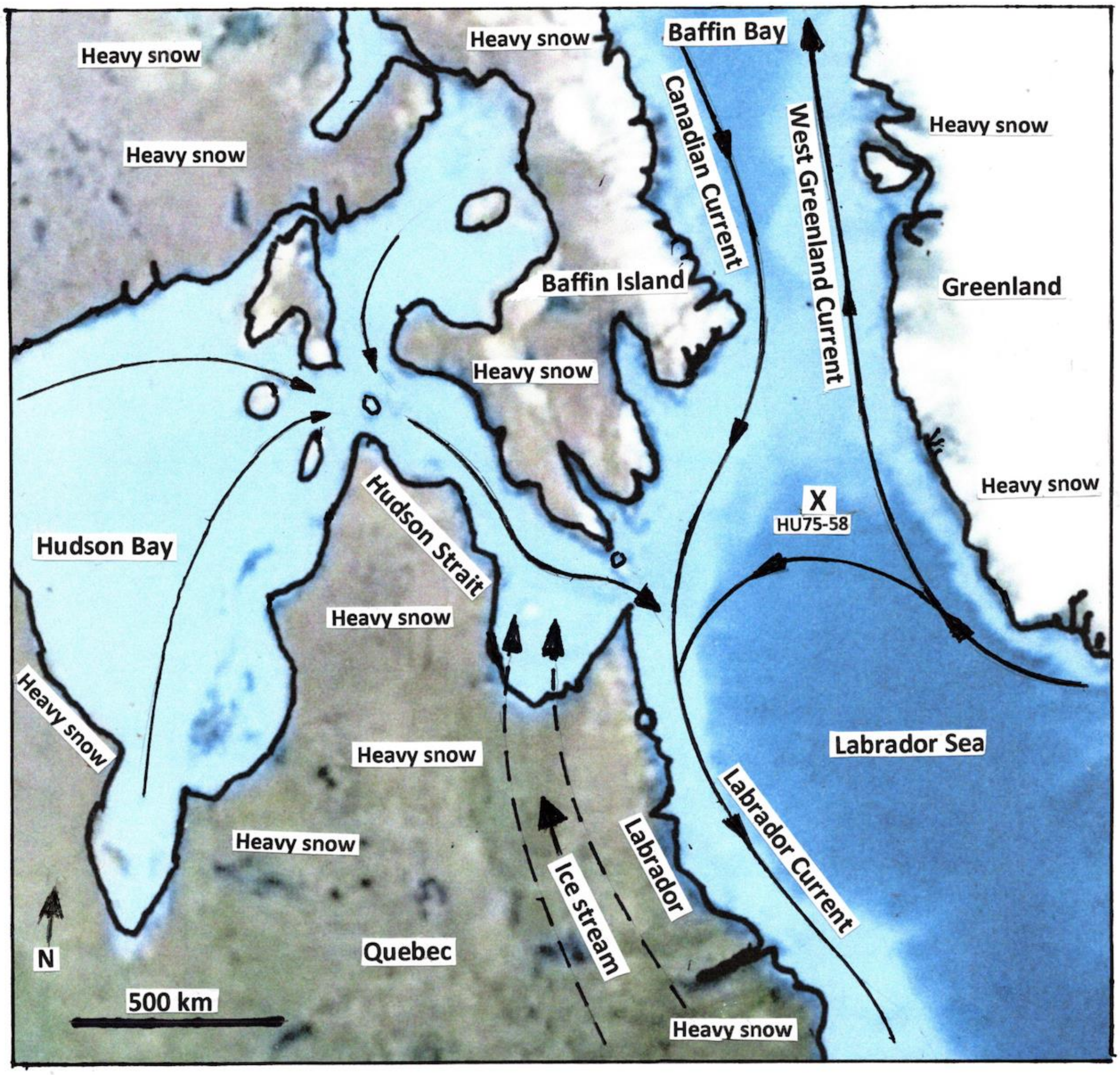

Figure 3. Oceanic Currents in the region around the center of the low-pressure system of Figure 2. This set of currents existed during the first ~400 years after deep-water formation and heavy snowfall began and before Hudson Strait became blocked by the ice dam. Baffin Bay and the Labrador Sea were open all year. Hudson Bay and Hudson Strait were seasonally open. The enhanced amount of fresh water that drained from Canada through Hudson Strait into the Labrador Current of the Northern Gyre weakened the AMOC flow, giving Europe an Arctic climate. This killed temperate climate trees in Western Europe.

had stratified Baffin Bay. However, this cold inflow would not explain the warmer subpolar sea surface temperatures west of southern Greenland at the beginning of the Last Ice Age[1]. Moreover, the interglacial AMOC flow oscillates with a 1,500 year period[8,9]. Therefore, its critical maximum flow could not have been maintained for more than a few hundred years.

3.2 Strong formation of deep water at the north end of Baffin Bay.

The water at the south end of Baffin Bay already contained a small amount of warmer and more saline water

that had been carried northward by the West Greenland Current after minor mixing with the Irminger Current arm of the Northern Gyre (Fig. 1). In contrast, the Atlantic water coming in through the Nares Strait from the polar ocean may have been close to 0˚C and 33 parts per thousand of salinity[10]. However, at this low temperature, winter cooling would have had little effect on its density of 1.02654 gm/cm^3. A simple calculation using handbook values suggests the effectiveness of the higher salinity of the lower latitude Irminger Current.

With Interglacial climate conditions, the Irminger Current values in the Last Interglacial were likely close to those of today: about 8˚C and 35 parts per thousand of salinity[10]. Its density would have been 1.02287 gm/cm^3. Cooling to 0˚C would bring the density up to 1.02831 gm/cm^3 with a difference of 0.00077 gm/cm^3. Lateral mixing may have reduced this difference somewhat, but it would still indicate a high rate of deep-water formation. The 8˚C higher temperature at the south end of Baffin Bay would have made the dominant Labrador Low pressure system with its extreme amounts of precipitation quite plausible. Much of the resulting heavy precipitation that did not contribute to rapid ice sheet growth was retained in the giant Lake Zissaga, which was accumulating behind the ice sheets in Canada[11] while the Hudson Strait ice dam blocked drainage through Hudson Strait. Two significant climate effects resulted. In one, the glacial ice buildup in Canada continued for ~3,600 years. In the other, the ice dam in Hudson Strait prevented fresh water originating west of the strait from entering the Northern Gyre. This kept the AMOC flow strong and kept Eurasia free of new glaciation during that time. The strong flow of saline replacement water from the Irminger Current reversed the flow through the Nares Strait, and made the Baffin Bay and Labrador Sea climate independent of minor variations of the strength of the AMOC flow. Evidence for the warmer Irminger Current flow was reported by R.H. Fillon[1] who found a rise in abundance of sub polar foraminifera from 7% of interglacial time to >50% at the beginning of the Last Ice age. This data came from deep sea core HU75-58, halfway between southern Baffin Island and Greenland and about 1,600 km from the north end of Baffin Bay where deep water formed (Figs. 2 and 4).

3.3 ~400 years of extremely rapid glacial ice sheet growth.

The cold land that surrounded most of the sea west of Greenland and the much warmer open water throughout the year at the southern end of Baffin Bay would have created a persistent and very strong atmospheric low-pressure system, with a regional increase of annual snowfall that may have been as much as eight times the present day amount[3]. Much of this precipitation drained out through Hudson Strait (Fig. 3), mixed into the Northern Gyre, lowered its salinity, and reduced the AMOC flow. This cooled the sea northeast of Greenland and steered storm paths to the grounded ice sheet covering the shallow Barents Sea. The great amount of annual precipitation that did not melt and reach the ocean accumulated in all of the growing ice sheets, and caused a rapid world sea level fall of 2.4 m as measured by surveys on uplifted Barbados[3]. This sea level fall occurred in approximately 400 years as suggested by the short interval in which the pollen of temperate climate trees was absent in sediment from a lake in Germany[2]. In this sediment core, the different types of pollen grains were counted in each interval of 200 years. However, only one interval had no pollen from temperate climate trees. The preceding and following intervals had significant counts, but could have had adjacent barren ~100-year intervals. Therefore, a more likely duration of the very cold interval was ~400 years, in which world sea level fell 2.4 m. This rapid fall was terminated by the development of an ice dam within Hudson Strait near its east end. The dam was a consequence of an ice stream flowing into the strait (Figs. 3 and 4). The ice stream was fed by the heavy snowfall on the Labrador highlands adjacent to the warmer Labrador Sea. A result of the formation of the ice dam was the reduced drainage of fresh water into the Northern Gyre. This large reduction in fresh water restored a stronger AMOC flow, and returned a mild climate to western Europe. The stronger AMOC also caused the deglaciation of the marine-based ice dome on the Barents Sea and ice elsewhere in Eurasia, producing a halt to the falling sea level, which caused a step in the coral surface of Barbados[3]. Northern Hemisphere

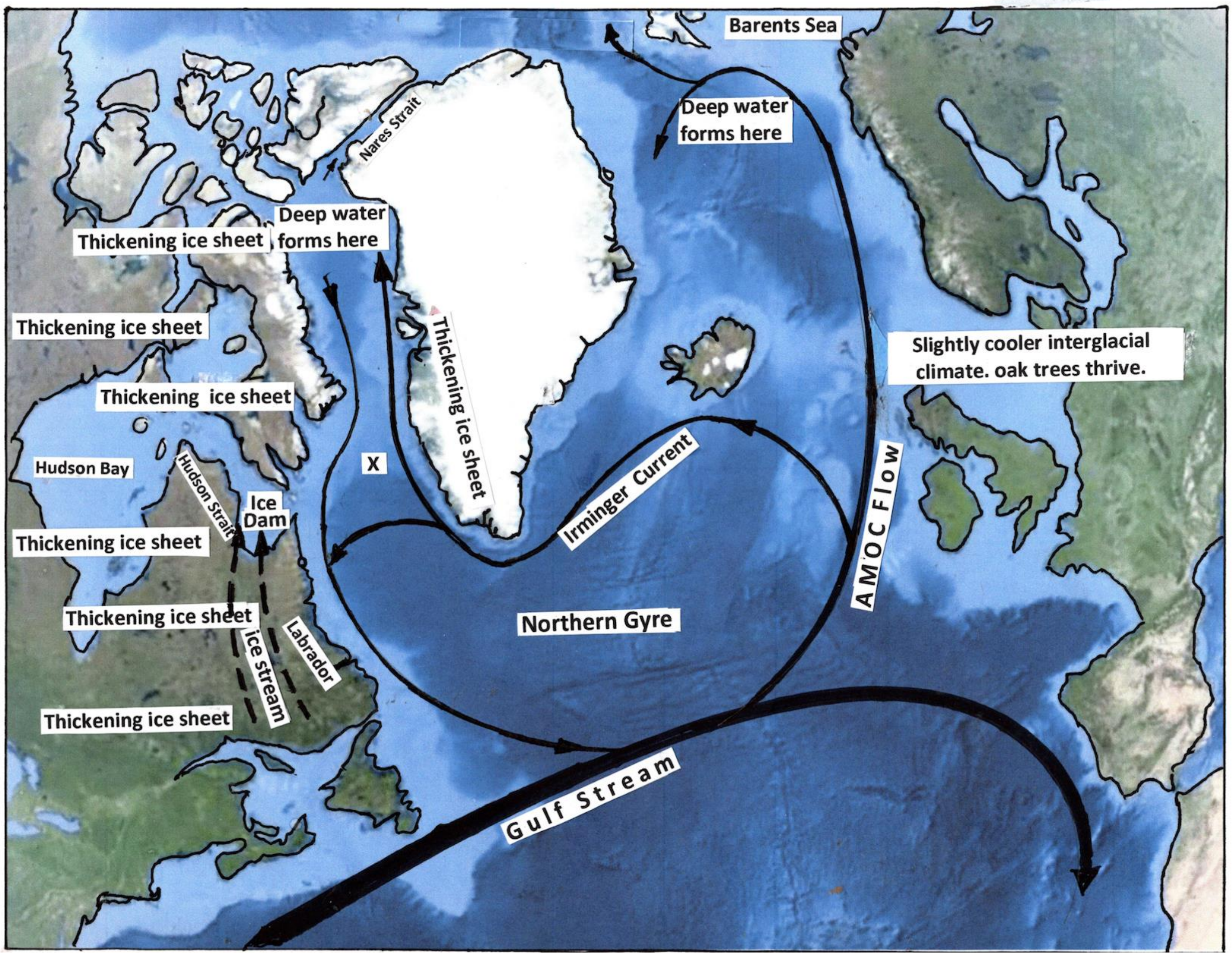

Figure 4. Principal currents after formation of the Hudson Strait ice dam as Canadian ice sheet growth continued. Absence of fresh water draining through Hudson Strait enabled a stronger AMOC flow and a return of interglacial warmth to Europe. Strong deep-water formation occurred at two locations for the next ~3,600 years until the ice dam was destroyed.

ice sheet growth continued for the following ~3,600 years until the Hudson Strait ice dam was destroyed. During this time, the doubly enhanced deep-water formation would have minimized sea ice around the Antarctic continent, increased snowfall there, and contributed to the rapid rate of world sea level fall.

4. Ending deep-water formation in Baffin Bay.

After the Hudson Strait ice dam formed, a somewhat cooler but mild interglacial climate continued in Eurasia as did Ice sheet growth in Canada. This caused a fall of world sea level at a rate of 2.7 m per thousand years, as measured by surveys of paleo sea level change on Barbados[3] and the time scale of pollen from temperate-climate trees from lake sediment in western Germany[2]. As Canadian glacial ice volume increased, the lack of drainage due to the ice dam allowed giant Lake Zissaga to accumulate behind the ice dome buildup in northern Canada[9]. Eventually the rising lake level began to overflow into Hudson Strait between the higher elevations of Labrador and Baffin Island. The fresh water flow destroyed the ice dam[3], probably after a few decades of erosion. The resulting flood of melting icebergs lowered the salinity of the entire Northern Gyre. The resulting lower salinity of the Irminger Current then stratified Baffin Bay and ended its deep-water formation. The AMOC flow was also greatly reduced by the lower salinity of the gyre and probably brought an arctic climate to northern Eurasia. Nevertheless, the quite zonal circulation in the northern North Atlantic steered storm paths away from the ice sheet regions, causing a deglaciation. The result was a world sea level rise of 3.8 m, as measured by Barbados surveys of elevation differences between wave-cut steps[3].

5. Why Baffin Bay deep-water formation was necessary to start the Last Ice Age.

The Last Ice Age began with a climate change from the relatively dry interglacial climate like today in northeastern Canada to a climate of almost continual snowfall associated with the persistent Labrador Low atmospheric pressure system. The Labrador Low was generated by the warmth of the water drawn from the Northern Gyre. Without this warmth and salinity in the water drawn into the West Greenland Current from the Irminger Current to replace surface water sinking at the north end of Baffin Bay, the temperature of the sea everywhere west of Greenland would have been little warmer than that of today. No strong Labrador Low with its heavy snowfall would have occurred, and no world sea level fall of 2.4 m in only ~400 years would have occurred. The strong deep-water formation at the north end of Baffin Bay is therefore seen as the second factor that ensured the initiation of the Last Ice Age after elimination of Baffin Bay stratification.

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J.A.Y. Johnson did a critical reading of the manuscript. W.A. Johnson proofread the manuscript. C.D. Gallup measured the radioisotope age of the large coral head that grew at the time of the collapse of the Hudson Strait ice dam shortly after 117 ka BP.

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