Testing the Freshwater Routing Hypothesis for Abrupt Climate Change with a Hudson River Paleodischarge Record

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TESTING THE FRESHWATER ROUTING HYPOTHESIS FOR ABRUPT CLIMATE CHANGE WITH A HUDSON RIVER PALEODISCHARGE RECORD

An undergraduate thesis

by

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Abstract

The mechanisms of abrupt climate change during the last glacial period are not yet fully understood. The objective of this research is to use oxygen isotope and magnesium/calcium ratios from foraminifera in a marine sediment core <200 km southeast of New York City (Ocean Drilling Program 174 Site 1073A) to test the hypothesis that changes in freshwater run-off patterns during intermediate extensions of the Laurentide Ice Sheet caused abrupt climate change by disrupting the Atlantic thermohaline circulation. The combination of foraminiferal $\delta^{18}O$ and Mg/Ca yields salinity as an isolated variable, which is used as a proxy for Hudson River discharge through ~42,000-28,000 years ago. This thesis reviews the literature on abrupt climate change and compares the Hudson River paleodischarge record to established records of abrupt climate events observed in Greenland ice cores. It concludes that a higher resolution of data points is required to evaluate the impact of Hudson River discharge on abrupt climate change.

Acknowledgements

I thank my advisor, Jeremy Shakun, for his guidance on this project. It has been an honor and a pleasure to work with such an obviously blossoming new professor. He dealt with long-winded emails, unannounced pop-ins, and my propensity to create distractions. I also thank him for allowing me to use his lab, bringing me to my second point: I am indebted to the Mudlab of Devlin Hall. It earned the fond title in October of 2014, when the room became a sacred space for therapeutic mud-sieving. The Mudlab was fundamental to the completion of this project because it provided a home base. I thank Lab Owl for keeping watch over lab entropy. I thank the inspiring crew of grad students for setting a great example. I thank my parents for providing opportunity and an open mind. Finally, I thank Marian, Tej, Johnny, Chris, Kristina, and all of my friends for their capacity to listen and let be.

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CHAPTER 1 – INTRODUCTION

The Problem of Abrupt Climate Change

In the early 1990's, groundbreaking analysis of ice cores through the Greenland Ice Sheet revealed a pattern of abrupt climate changes in the North Atlantic. For years, geologists have known that dramatic climate changes occurred in the Earth's past. Evidence is found in the presence of glacial deposits in non-glaciated regions of the U.S., or in the presence of shallow marine carbonate deposits from tropical climates in present day Europe. However, many questions about the frequency, rate, and magnitude of such changes remain. A major step in addressing questions about climate change was taken by studying the ice cores from the Greenland Ice Sheet. The ice cores record past climate over time at high resolution, and indicate the presence numerous, dramatic climate swings, each occurring rapidly. Imagine a 15 °C climate change occurring within 30 years—the climate of Boston would become the climate of Atlanta—and consider that these changes happened *repeatedly* throughout the last ice age (Alley, 2000). This is the phenomenon of abrupt climate change, and these events occurred at least every few millennia.

In contrast to the climate of the last glacial period, the present-day climate is notably stable. We are currently in the Holocene, the ~12,000 year period since the end of the last glaciation that features a relatively warm and consistent climate (Alley, 2000). Despite representing a departure from the climate of the last 110,000 years, it is precisely during the Holocene that humans have thrived. Modern civilization benefitted from a climate that remains roughly the same from generation to generation, and now assumes it. The existing global infrastructure reflects our confidence in consistent climate and sea level over time, as the biggest population centers in the world are found along coastlines. Even in the face of anthropogenic climate change, many believe that the changes will occur slowly enough that humans will have time to adapt without great loss. Yet, the ice core records tell a different story, one where stability is the exception rather than the norm. We now know that the climate has the ability to change dramatically over societally relevant periods of time. It is therefore critical to understand the mechanisms that cause such changes.

Testing the Freshwater Routing Hypothesis as Mechanism for Abrupt Climate Change

Much debate exists around the mechanisms of abrupt climate change in the last glacial period. Numerous hypotheses have been proposed, and many focus on changes in the thermohaline circulation (Clark et al. 2001; Rahmstorf, 2002; Broecker, 1992, 1994). The thermohaline circulation (THC) is an ocean current system that distributes heat around the globe, exhibiting strong control over climate in the North Atlantic (Alley, 2000). Because of its large influence, it is reasonable to hypothesize that changes in THC create changes in the climate of the North Atlantic. Additionally, there is geologic evidence to support that the THC has changed in the past, displaying its ability to “turn off” and “turn on,” (Ganopolski and Rahmstorf, 2002). The changes from “off” to “on” have occurred quickly, on the decade-scale of abrupt climate change, which agrees with the time constraints for an abrupt climate change event. The potential for changes in THC to occur quickly and with high climatic impact provides a plausible mechanism for abrupt climate change. However, even if changes in THC are intimately linked to abrupt climate change, paleoclimatologists still lack a mechanism that *controls* the changes in THC.

The research detailed in this thesis addresses the hypothesis for abrupt climate change proposed by Clark et al. (2001), that routing of glacial meltwater from the Laurentide Ice Sheet causes changes in THC and therefore causes abrupt climate change. It hinges on the idea that the THC can be shut down when its overturning process is disrupted. When the THC is "on," warm waters flow from the tropics to the North Atlantic, and become cold, salty, and dense in the North Atlantic, leading to sinking, known as North Atlantic Deep Water (NADW) formation (Clark et al., 2002). The hypothesis assumes that if less dense freshwater were to mix with sinking saltwater, it would prevent the sinking process and shut down the entire THC, akin to sticking a wrench in a conveyor belt at the location of overturning (Alley, 2000). Glacial meltwater from the Laurentide Ice Sheet serves as the "wrench," disrupting the downwelling process. A glacier of the size of the Laurentide Ice Sheet creates a high volume of annual meltwater. According to the hypothesis, oscillations in glacial advance and retreat determine the route of freshwater drainage, causing a shutdown of the THC whenever freshwater drains into the North Atlantic, as opposed to the Gulf of Mexico (Clark et al., 2001). Each time glacial meltwater routed towards the North Atlantic, an abrupt climate change event occurred, and when freshwater routed elsewhere, the THC started up again, creating another abrupt climate change event.

This thesis tests the freshwater routing hypothesis. This research has been intentionally modeled after Hill et al. (2006), which studied Mississippi River discharge into the Gulf of Mexico, and compared paleodischarge with the record of abrupt climate change events in order to evaluate the freshwater routing hypothesis. The data set produced is similar to the record produced in Hill et al. (2006) so that they can be easily compared with each other, as they should be agreeable if the freshwater routing hypothesis is valid. This research studies freshwater drainage patterns in the Atlantic Ocean, near the mouth of the Hudson River. Using foraminifera stable isotopes, a record of paleosalinity has been created from a sediment core <200km off the coast of New York City, a site that records changes in freshwater flow from the Hudson River. The reconstructions will be used to compare changes in paleosalinity with the known occurrences of abrupt climate change from the Greenland ice core. Analysis of the data either supports or detracts from the feasibility of the freshwater routing hypothesis. This report develops an understanding of the freshwater routing hypothesis in detail, and frames the hypothesis within the context of the climate patterns of the last glacial period.

CHAPTER 2 – BACKGROUND

Climate Patterns of the Last Glacial Period

The analysis of the Greenland ice core record revealed the history of abrupt climate changes throughout the last glacial period. Paleoclimatologists sought to explain a) the mechanisms by which abrupt climate change occurs and b) the causes of these mechanisms. The freshwater routing hypothesis is one such mechanism, and it now needs to be understood within the context of the climate feedbacks, thresholds, and globalizers that control the climate system. The following section details the observed climate patterns of the last glacial period.

Milankovitch Cycles

Milankovitch cycles are the patterns of the earth's orbit and movement around the sun. They determine the distribution of solar radiation that the earth receives over time, influencing climate patterns and seasonal variation. Because of their control on climate, they are relevant in studying paleoclimate, global ice volume, and heat distribution networks such as THC. There are three main patterns in the Earth's orbital variation (Figure 1).

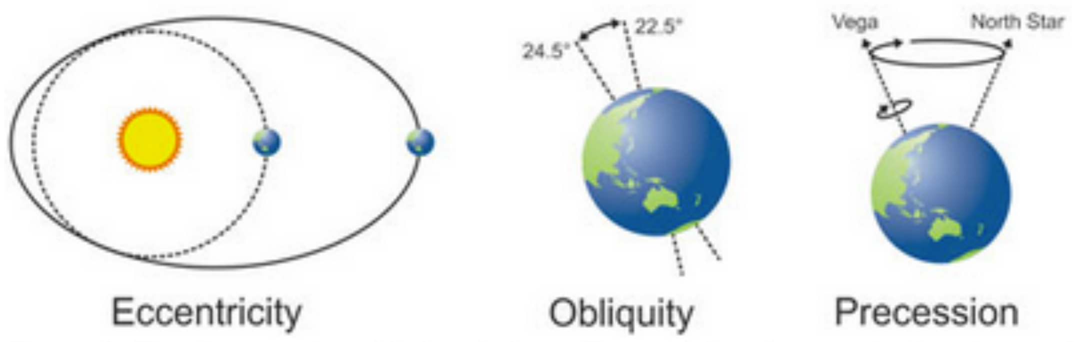

Figure 1. Visual representation of the Milankovitch cycles. Eccentricity, obliquity, and precession are three main orbital variations (Cook, 2014).

The longest cycle is orbital eccentricity, the phenomenon of how the earth's orbit around the sun changes from round to eccentric ("flattened") and back every 100,000 years (Alley, 2000). Over the past 600,000 years, there have been ice ages observed in the paleoclimate record every 100,000 years that are linked to orbital eccentricity (Hays et al., 1976) (see Figure 2). Eccentricity impacts the length and intensity of seasons, allowing for tens of thousands of years with short, cool summers when ice can grow, followed by a short stretch of interglacial climates that have long, warm summers, where ice retreats. The more eccentric orbit leads to glacial advance, and the rounder orbit causes glacial retreat. The second feature is obliquity, or tilt, where the angle of the earth's axis gradually cycles between 22.2° and 24.5° and back every 41,000 years (Alley, 2000). The lower the angle of obliquity, the more evenly solar radiation is distributed about the earth. Seasons are the product of one pole leaning closer to the sun for part of the year, and further in the other, so lower obliquity creates minimal heat differences between seasons. A higher obliquity gives more increases proximity of the poles to the sun, creating a more intense energy difference between seasons and "stronger" seasons. The third variation is precession, which is the 23,000-year cycle of "wobbling" of the earth's axis. Precession determines what hemisphere is in what season at a given time in the earth's orbit, creating gradual variation between a northern hemisphere summer when the earth is far from the sun (modern day) to a northern hemisphere winter when the earth is far from the sun (~10,000 years ago) (Alley, 2000). Milankovitch cycles do not affect the *total* solar radiation the earth receives, but they affect where and during what season solar radiation is received, shaping the pattern of ice age cycles observed in the geologic record (Hays et al., 1976).

Dansgaard-Oeschger Cycles in Greenland Ice Core Record

The impetus for paleoclimate research of abrupt climate change arose from the Greenland ice cores. Between 1989 and 1992, two cores were drilled into the Greenland Ice Sheet, the Greenland Ice Core Project (GRIP) and the Greenland Ice Sheet Project 2 (GISP2). Glacial ice serves as an excellent paleoclimate recorder because as snow accumulates, it traps air between ice crystals that represent the atmospheric conditions above the glacier at a given time. Snow accumulates seasonally, such that each layer of ice represents a particular year, allowing for absolute dating by counting layers (within error that increases with depth due to ice flow) (Dansgaard et al., 1993). Geochemical analysis of the ice and air bubbles at unprecedented resolution in the North Atlantic revealed the record of abrupt climate change above Greenland (Figure 2).

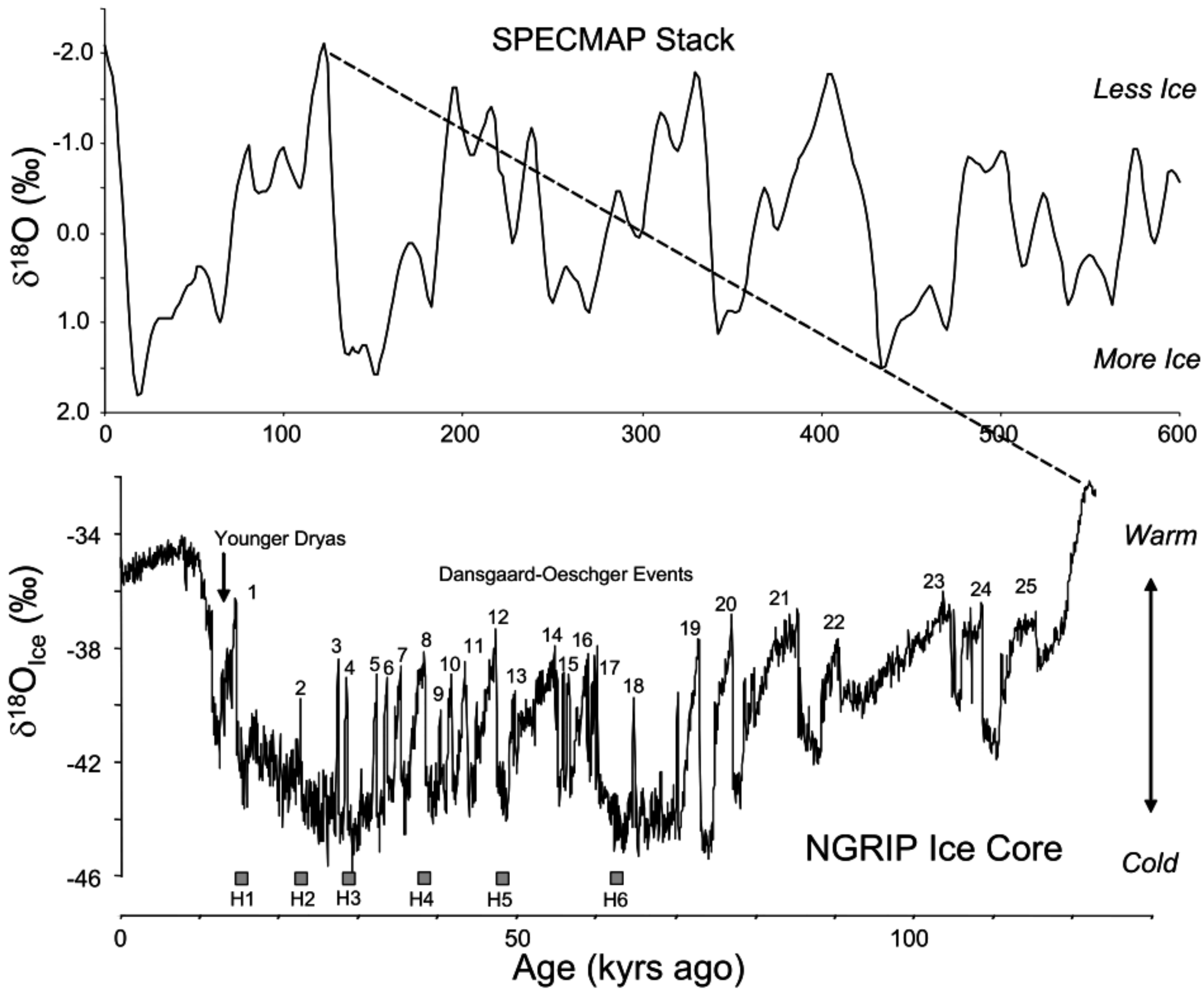

Figure 2. Top graph displays a composite δ^{18}O record from marine sediments, used as a proxy for temperature. Bottom graph depicts δ^{18}O record from NGRIP ice core, a proxy for air temperature. The marine sediment record was created from normalizing plankton foraminiferal isotope records, and it exhibits the typical resolution of marine sediments. The bottom graph was created by analyzing oxygen isotope ratios in glacial ice, and has a high resolution, such that century to millennial-scale variability in climate is visible. Dansgaard-Oeschger Events are labeled 1-25; Heinrich events are labeled H1-H6, [Clement and Peterson (2008) citing Imbrie et al. (1984) and North Greenland Ice Core Project Members, (2004)].

δ^{18}O is a measure of the ratio of oxygen isotopes, ^{18}O to ^{16}O, and can be used as a proxy for temperature in carbonate minerals, and as a proxy for temperature in ice. The top graph of Figure 2 represents a composite δ^{18}O record from plankton foraminifera in marine sediments. The bottom graph represents a $\delta^{18}O_{ice}$ record from the NGRIP ice core. The resolution of NGRIP $\delta^{18}O_{ice}$ is substantially higher than the δ^{18}O from marine sediments, alerting the scientific community to the presence of century to millennial-scale climate variability (Clement and Peterson, 2008). The final 8,200 years before present are stable, exhibiting less than 5 °C of change from any one point to another. The evidence from the Greenland ice cores contrasted the long-standing view that climate changes slowly over time (Alley, 2003).

Numerous times throughout the ice core, large changes in $\delta^{18}O_{ice}$ occurred in short intervals, telling of an abrupt climate change event above Greenland. As seen in Figure 2, there is a period of abrupt warming to a local temperature maximum, a period of slower cooling, and then a period of rapid cooling, with each temperature maxima given a number, 1-25 (Clement and Peterson, 2008). The repeating maxima became known as Dansgaard-Oeschger (DO) events (Bond et al., 1993; McManus et al., 1994; Dansgaard et al., 1993), and they occurred 25 times during the last glacial period. Bond et al. (1993) recognized that DO events occurred in groups, where one local temperature maxima would be followed by progressively cooler local temperature maxima, and progressively cooler local temperature minima. At a certain point, the coolest DO event in a group occurred, and it would be followed by a local temperature maximum higher than the previous one, indicating the beginning of a new cycle of progressively cooler DO events. Each cluster of progressively cooler DO events is called a DO cycle, and one cycle takes between 5-12 kyr (Bond et al., 1993) (Figure 3). Furthermore, the end of each DO cycle also coincides with a unique stratigraphic deposit of Ice-Rafted Debris (IRD) found in sediment cores across the North Atlantic (Heinrich, 1988). These deposits became known as Heinrich Events and are labeled 1-6 in Figure 2. Together, a DO cycle

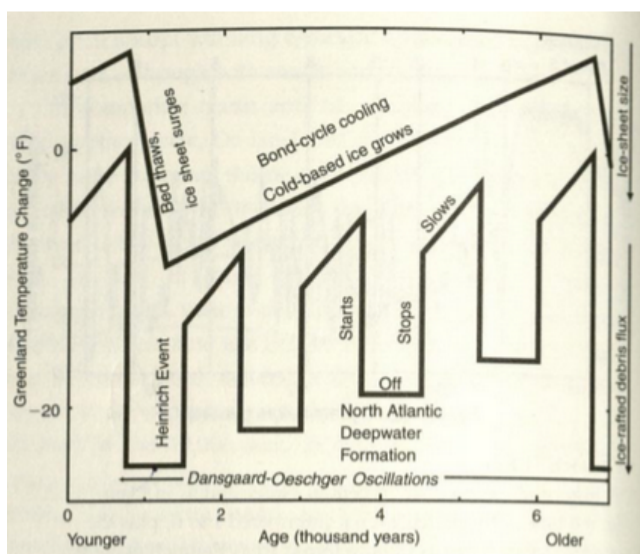

Figure 3. Schematic representation of temperature and age relationships for DO events, DO cycles, Heinrich Events, and the Bond cycle (Alley, 2000).

culminating in a Heinrich event became known as a Bond cycle, as observed by Bond et al. (1993).

The observed temperature oscillations above Greenland were confirmed to represent larger-scale climate variability when studies of ocean temperature displayed similar oscillations. Bond et al. (1993) created a record of North Atlantic sea surface temperatures from marine sediments during the last glacial period and compared it to the ice core record of DO cycles, concluding that the rate of change of ocean temperature matched the rate of change in the ice core, establishing the link between ocean and atmosphere. McManus et al. (1994) used high-resolution records of forams and ice-rafted debris from two cores in the North Atlantic to create a surface-ocean temperature record from 65,000-110,000 years ago, finding that their data exhibited DO cycles in good agreement with the GRIP record. The confirmation of the link between ocean temperatures and DO cycles was significant because it proved that the millennial-scale oscillations in Greenland $\delta^{18}O_{Ice}$ applied to large-scale oscillations of the greater North Atlantic climate.

Although the presence of DO events in the North Atlantic during the last glacial period is well-documented, the mechanism for DO events remains debated. They are either explained by internal oscillations in the climate system or by external forcing, and have two perplexing characteristics: 1) they have a regular periodicity and 2) they appear at varying geographic extents. As to the first, DO cycles occur with striking regularity, occurring on a ~1,470-year period (Rahmstorf, 2003) (Figure 4). The precision of the "internal clock" for DO events is distinctly atypical for a climate mechanism, as oscillations within the climate system tend to be highly irregular due to its complexity. The climate system has a large number of degrees of freedom, and the unstable process of atmospheric circulation affects its patterns (Rahmstorf, 2003).

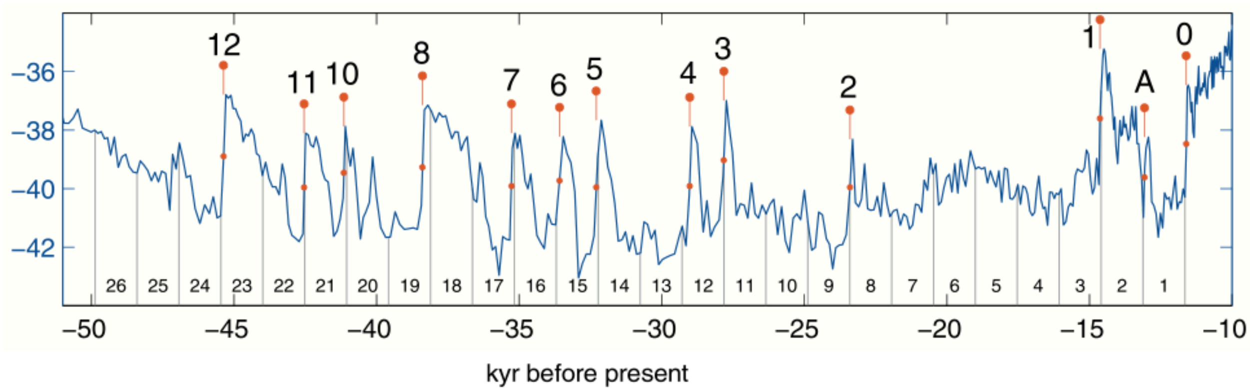

Figure 4. Depicts DO events through time with intervals of 1,470 years marked by grey bars, numbered 1-26. DO events occur with a periodicity of ~1,470 years (and multiples of 1,470 years) consistently (Rahmstorf, 2003).

Orbital forcings, however, tend to be highly regular, leading some to believe that DO events are caused by the earths interaction with the sun (Braun et al., 2005; Rahmstorf, 2003). Rahmstorf (2003) found that the variation is ±8% around multiples of a 1,470-year period. The most interesting aspect of DO periodicity is that it has low "clock error," in that it is a very accurate clock. Clock error occurs when a clock is late at given time, and the single event of lateness makes all subsequent times late. Rahmstorf (2003) finds the clock error to be <7% of the period, a very low value. He finds it very unlikely that an internal climate feedback would be so accurate, and instead proposes that DO cycles are paced by an external cycle, rather than being a controlled by internal feedbacks. On the other hand, the orbital forcing hypothesis is challenged by the lack of an identifiable 1,470-year solar cycle for forcing DO events. One study, Braun et al. (2005), showed that in a glacial climate, periodic freshwater input into the North Atlantic during known solar cycles of ~87 and ~210 years created a 1,470 year spacing of rapid climate shifts similar to DO events.

It also remains a question as to what degree do changes in climate above Greenland reflect changes in the North Atlantic and the globe. Using various temperature proxies of $\delta^{18}O$ of planktonic foraminifera, magnetic susceptibility, dust, pollen, etc., numerous records of paleotemperature have been created, especially in the North Atlantic (Figure 5). Solid circles represent the location of paleotemperature records that exhibit DO cyclicity, and open circles represent locations where DO cyclicity is unclear or absent. The majority of records that exhibit DO cyclicity with ≤ 200 year resolution are found in the North Atlantic, with the second-highest concentration observed in China. The southern hemisphere contains few sites at this resolution, lacking enough data for meaningful conclusions. At the 200-500 year resolution, the North Atlantic continues to exhibit the presence of DO cyclicity, while the southern hemisphere continues to be low in data. There are more occurrences of observed DO cyclicity at this resolution in the southern hemisphere, but to get a comparable data pool to the northern

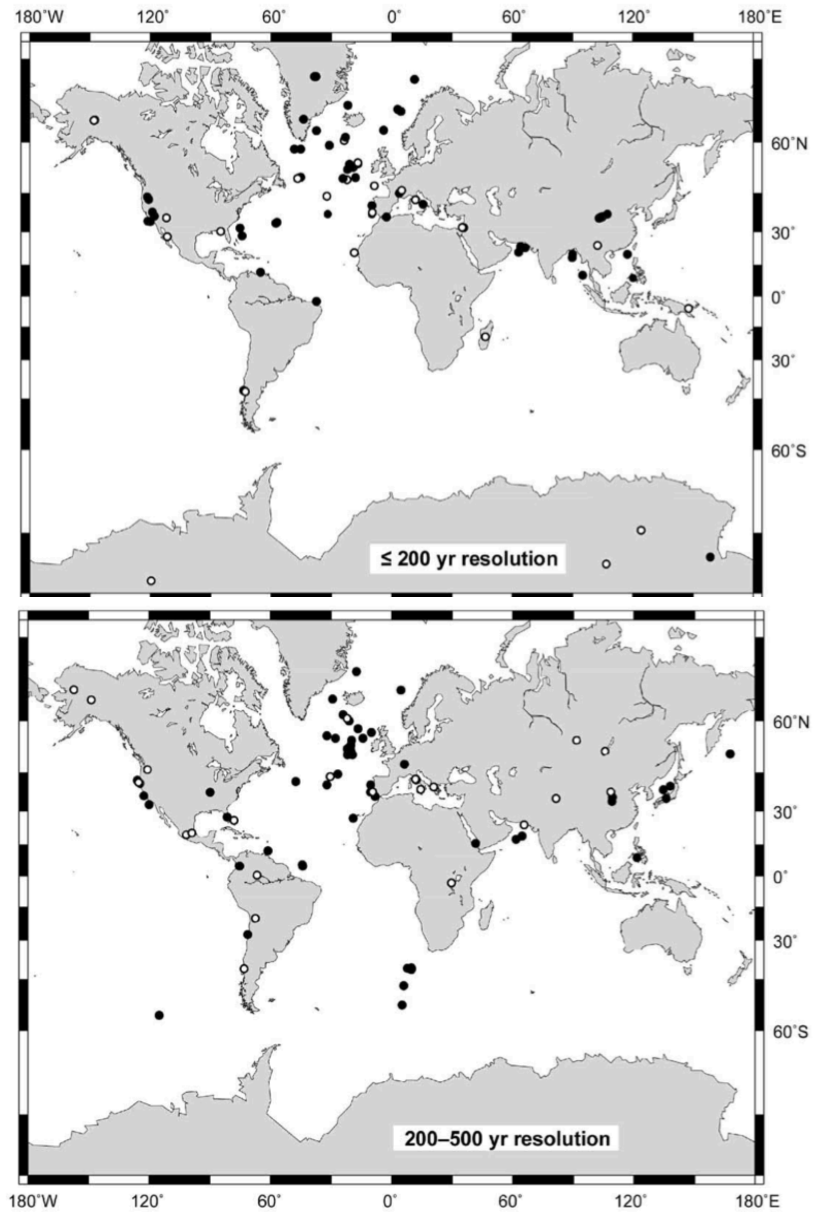

Figure 5. Map depicting 183 paleotemperature records created from various methods at high resolution and a lower resolution. Solid circles indicate locations where DO cycles are observed; open circles indicate locations where DO cyclicity is unclear or absent (Voelker and Workshop Participants, 2002).

hemisphere, more data is needed. Additionally, it can be argued that more data within the northern hemisphere is needed to make conclusions about whether DO events extend outside of the North Atlantic (Wunsch, 2006). Lingering questions about DO cycles pose challenges to identifying a mechanism.

Heinrich Events

Heinrich Events are characterized by massive releases of icebergs into the North Atlantic from the collapse of ice sheets (Heinrich 1988; Hemming, 2004). The icebergs disseminate out across the North Atlantic after the collapse of an ice sheet. Upon melting, they leave distinct sedimentary layers of IRD. Heinrich layers exist across the North Atlantic, speaking to the volume of ice discharged and cool climate at the time that allowed them to travel great distances before melting (Figure 6).

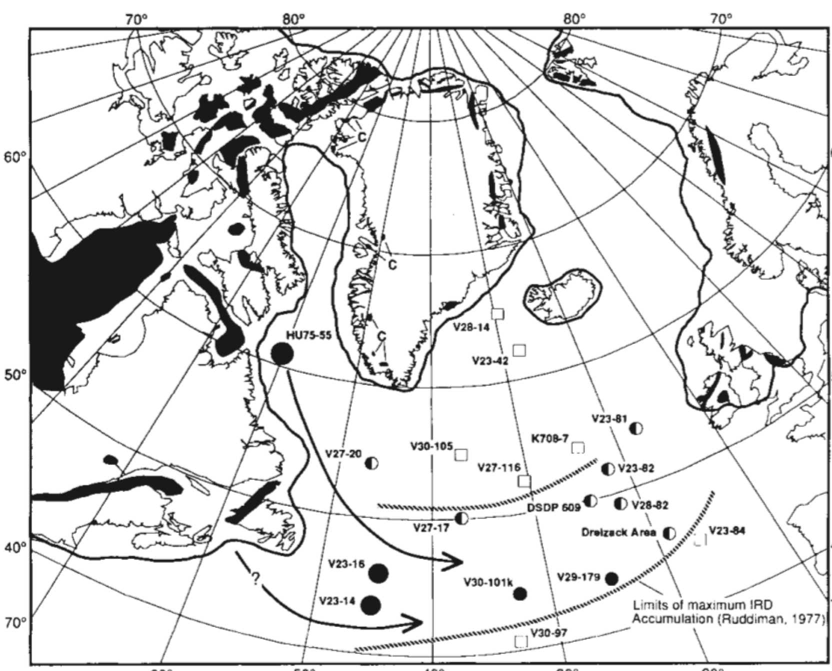

Figure 6. Map tracing the route of icebergs discharged during Heinrich Events. Shows location of cores that contain Heinrich ice-rafted debris deposits. Filled circles indicate carbonate-rich IRD in all deposits. Half-circles indicate carbonate-rich IRD in only some deposits. Open squares represent no carbonate-rich IRD in any deposits. The solid black patterns indicate the distribution of carbonate bedrock (Bond et al., 1992).

The arrows in Figure 6 show the route of icebergs discharged during Heinrich events. The circles and squares represent different sediment cores, and are distinguished by the sedimentology at each site. The different lithologies provide information about provenance, which is used to source the ice to the Laurentide Ice Sheet in the Hudson Strait region. The widespread detection of Heinrich events throughout the North Atlantic illustrates the large the volume of icebergs released, and their ability to traverse such great distances over the Atlantic indicates that a particularly cool glacial climate dominated the North Atlantic during Heinrich events. The lines that delineate maximum IRD accumulation reveal the average path taken by the icebergs, as the maximum amount of material related to the Hudson Strait is found between these boundaries (Bond et al., 1992).

The lithology of Heinrich deposits matches the sediment entrained by the Laurentide Ice Sheet (LIS) in the Hudson Strait, indicating an origin for Heinrich icebergs (Bond et al., 1992). Carbonate deposits underlie the LIS in northern Canada and in the Hudson Strait. Glacial processes of the LIS at the Hudson Strait entrain lithic grains of limestone, dolostone, and Precambrian bedrock from the North American craton that are unique to the region, explaining the source for Heinrich event. The provenance also addresses how these lithic grains uncomformably deposited on to deep ocean sediments otherwise dominated by muds. Heinrich deposits feature a radical drop-off in foraminifera abundance and a local minimum in the $\delta^{18}O_{Seawater}$ record (Broecker, 1994). Heinrich deposits exhibit stark increases in the quantity of lithic grains, as seen in the vertical profile of a DSDP Site 609 (Figure 7). Heinrich deposits are numbered H1-H6. The quantity of lithic grains (>150 um) increases substantially with a sharp contact at the base, implying abrupt deposition. Although the foraminfera-to-lithic grains ratio decreases drastically in a Heinrich layer, polar foraminifera (*neogloboquadrina pachyderma*) are the most abundant species in the deposit, indicating that polar waters extended to low latitudes during Heinrich events (Bond et al., 1992).

Various mechanisms have been proposed for the cause of Heinrich Events. They consistently occur at the end of a DO cycle, at the local minima for temperature, and are always followed by an abrupt warming (Hemming, 2004). The presence of polar foraminifera, low $\delta^{18}O$ values, and sequentially cooler DO events indicates that Heinrich Events are tied to maximum extensions of ice sheets at the coldest periods of the last glaciation. Debate occurred over whether Heinrich events cause the climate changes, or merely reflect them. It was initially considered that the freshwater released from the melting of icebergs created cooling by causing a shutdown of the thermohaline circulation, a distributor of heat in the North Atlantic

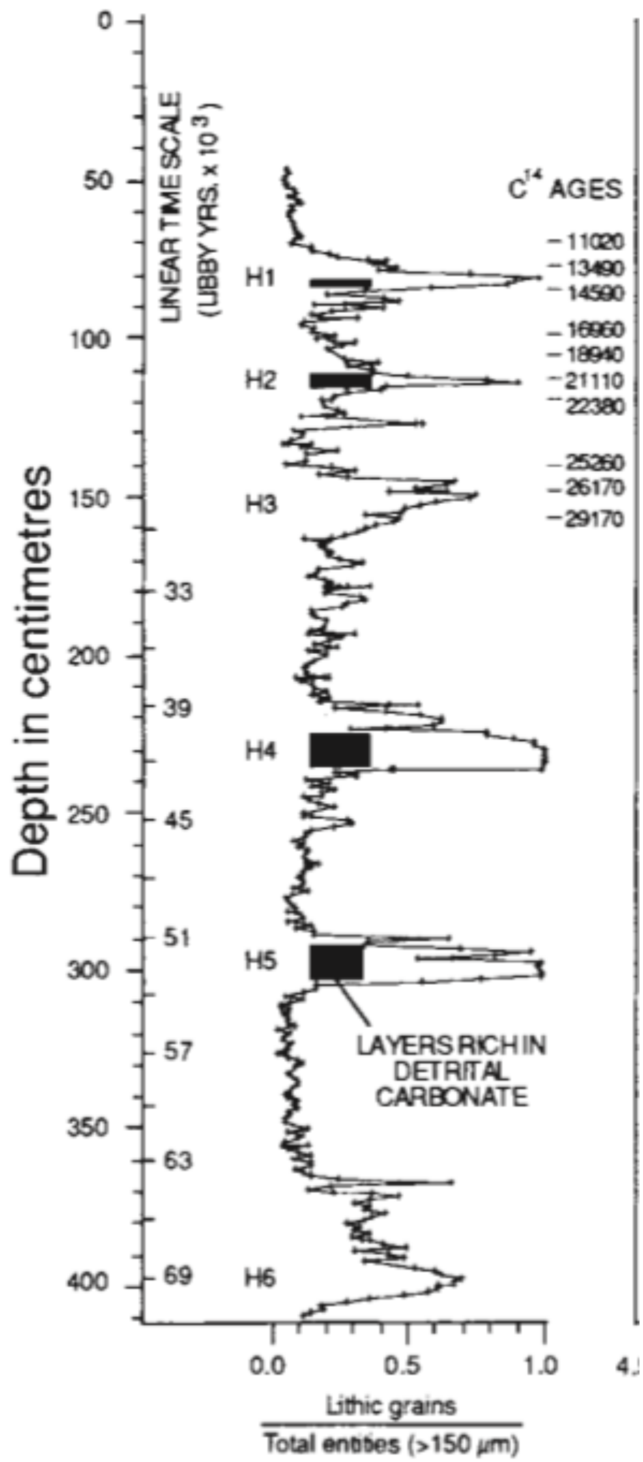

Figure 7. Vertical profile of sediment core from DSDP Site 609. Depth in cm vs. quantity of lithic grains, measured by total particles of size >150 um (Bond et al. 1992).

(Broecker, 1994). Similarly, Bond et al. (1993) explain the abrupt warming and occurrence of a new DO cycle after a Heinrich event with an increase in thermohaline circulation due to the large reduction of icebergs after the collapse of the ice sheets. They reason that increasing salinity in the water from reduced icebergs and ice sheet influence increases the intensity of thermohaline circulation, creating warming. Others conclude that Heinrich events are a product of internal ice-sheet mechanisms. MacAyeal (1993) argues for the binge-purge model for Heinrich events, where the series of cooler and cooler DO cycles culminates in temperatures so cold that ice sheets reach a size threshold and collapse (Figure 8). Basal melting occurs as geothermal heat accumulates from ice insulation and pressure is at an extreme high, such that conditions become suitable for liquid water. Water causes basal slip, and the ice sheet collapses, releasing the icebergs and dramatically reducing the thickness of the ice sheet, allowing for regrowth. The regrowth phase is the binge portion, and the collapse phase is the purge portion. This model has fallen out in contemporary understandings of Heinrich Events in favor of climate forcing models (Hemming, 2004; Marcott et al., 2011). Hemming (2004) leaves a definitive mechanism open-ended.

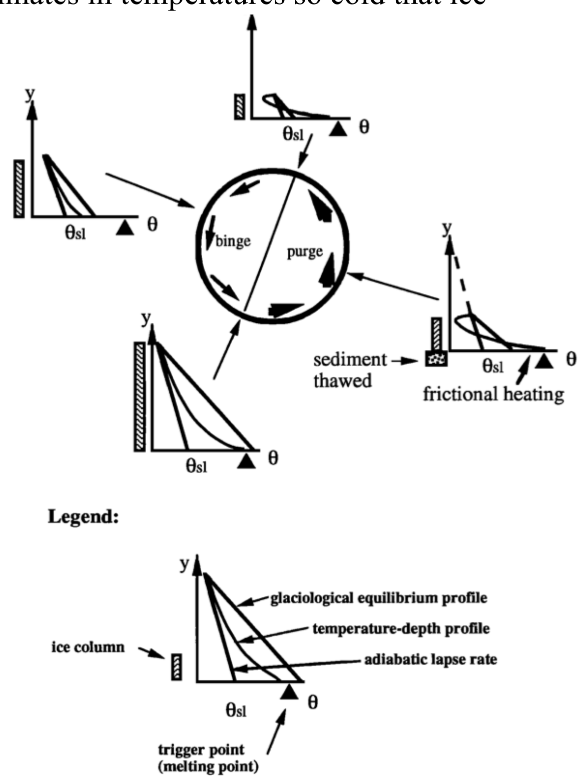

Figure 8. Conceptual view of binge-purge model of Laurentide Ice Sheet. Temperature-depth profile in an ice column (MacAyeal, 1993).

Younger Dryas Cold Event and Deglaciation

The end of the last glacial period was marked by distinct abrupt climate changes. Temperatures began to warm from the Last Glacial Maximum (~21,000 yrs B.P.), or the largest extent of the glaciers before they melted, progressing towards the stable, warm climate of the

Holocene. From ~14,600 to ~12,900 yrs B.P., a warming event occurred, similar in magnitude to DO events, known as the Bølling-Allerød (B-A) warm interval. Then, at ~12,900 yrs B.P., there was a rapid temperature drop, returning the Northern Hemisphere into glacial conditions until ~11,500 yrs B.P., known as the Younger Dryas (YD) cold interval (Rooth, 1982). After the YD, the climate warmed to present-day conditions. The climate signals of the last deglaciation are observed in numerous paleoclimate records in the Northern hemisphere (Carlson et al., 2007). The YD cold interval is of particular interest in studies of abrupt climate change because of its fresh geologic imprint. By nature of the YD as a cold minimum, glaciers have retreated since ~11,500 yrs B.P., leaving a sediment record of the YD over the course by deglaciation. The geologic signature of the YD is similar to Heinrich events, in that has a corresponding layer of IRD in sediment cores of the North Atlantic, leading some to call it Heinrich Event 0 (Bond et al., 1992). The paleoclimate signature of the YD is similar to a DO cycle, where an abrupt warming is followed by a return to stadial conditions.

The conventional mechanism to explain the YD is a shutdown of THC by freshwater forcing (Johnson and McClure, 1976; Rooth 1982; Broecker et al. 1989). During the B-A warm interval, the LIS retreated, causing the collapse of proglacial Lake Agassiz, where a proglacial lake is a body of water that forms around an ice sheet due to isostatic depression. Upon collapse of the lake as the glacier retreated, the water stored in the lake re-routed from the southern margin of the LIS and ultimately flowed into the St. Lawrence River basin. The removal of the LIS caused the size of the St. Lawrence River drainage basin to double, dramatically increasing freshwater flux into the North Atlantic at the mouth of the St. Lawrence River (Carlson et al. 2007). At the same time as this freshwater influx, paleoclimate records indicate a dramatic reduction in the strength of the Atlantic Meridional Overturning Circulation (AMOC), or THC.

The flux of low-density freshwater at the surface of the Atlantic disrupted AMOC, redistributing heat around the globe via bipolar seesaw (Broecker, 1998). Carlson et al. (2007) provides direct oceanographic evidence to support freshwater routing as the cause for the YD. They used ΔMg/Ca, U/Ca, and $^{87}Sr/^{86}Sr$ from planktonic foraminifera at the mouth of the St. Lawrence estuary to trace freshwater sources and confirm an eastward routing with an increasing freshwater flux at the time of the YD. They implicate meltwater routing as the cause abrupt climate change, arguing that it was substantial enough to reduce the strength of the AMOC to an "off" mode, creating the brief return to glacial conditions during the YD. Broecker et al. (1989) finds an agreeable salinity signal of YD in the Gulf of Mexico.

Studying the YD provides insight into deglaciation and processes of freshwater routing. Broecker et al. (2010) proposes that the YD is not an anomaly, but a key part of the global climate shifts from a glacial to an interglacial. However, if the YD is to cause a shutdown of AMOC, then there should not be observed fluctuations of AMOC during the YD. Such fluctuations are observed, creating a problem for an understanding of the YD as the abrupt climate event resulting from a large freshwater routing event due to the collapse of proglacial Lake Aggassiz. It implies that the observed climate oscillation occurred from a single flood, when single flood events from glacial meltwater were found not to be strong enough to influence AMOC (Meissner and Clark, 2006). They instead found that routing events over centuries to millennia cause millennial-scale climate variability. In contrast to previous understandings of meltwater routing during the YD, Carlson et al. (2007) found evidence in foraminifera of repeated intra-Younger Dryas routing events, and these events agreed with changes in AMOC. The data supports climate sensitivity to changes in AMOC as caused by meltwater flux to the Atlantic.

The last deglaciation also exhibits a warming event prior to the YD that coincides with a massive increase in sea level. ~14,600-12,900 years B.P., the last glaciation is punctuated by the B-A warm interval (Dansgaard et al., 1992) (Figure 9). The B-A warm interval begins at a sea level minimum and temperature minimum that developed the Older Dryas (OD). A spike in temperature, sea level, and rate of sea level rise occur around 14,600 yrs B.P., and this event became known as Meltwater Pulse 1A (MWP-1A), which marked the end of the last glacial period (Weaver et al., 2003). The dramatic temperature increase in a short period of time during the B-A warm interval bears similarity to a DO event, including the cooling afterward that leads up to the YD.

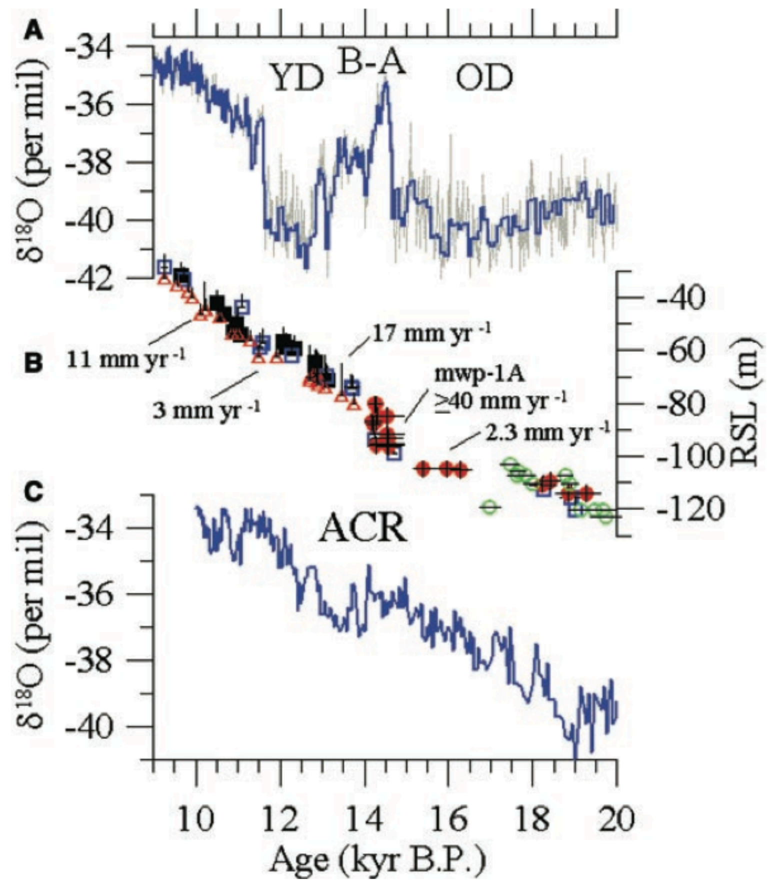

Figure 9. Record of climate and sea-level over the course of the last deglaciation. (A) exhibits the GISP2 record of d^{18}O, used a proxy for temperature. YD is the Younger Dryas, B-A is the Bølling-Allerød warm interval, and OD is the Older Dryas. (B) shows relative sea level (RSL) in meters on the right-hand side; it shows average rates of sea level rise for the periods 19 to 14.6, 14.6 to 14.1, 14.1 to 12.9, 12.9 to 11.6, and 11.6 to 6 kyr B.P. Data are depicted as cited in Weaver et al., (2003). Data are from Bonaparte Gulf (green open circles) (Yokoyama et al. 2000), Barbados U/Th dated corals (open blue squares) (Bard et al., 1990), Sunda Shelf, Tahini (open red triangles) (Hanebuth et al., 2000), and New Guinea (closed black squares) (Edwards et al., 1993). (C) shows the Byrd ice-core oxygen isotpe record from Antarctica on the same time-scale as the GISP2 record. ACR is the Antarctic Cold Reversal (Weaver et al., 2003).

The source of freshwater for MWP-1A remains contested. Weaver et al. (2003) found that the source of MWP-1A seems most likely to be the Antarctic ice sheet, rather than the LIS, which would cause a decrease in the strength of the AMOC and global cooling (Clark et al., 2001). Proxies indicate increased NADW formation and warming of North Atlantic during the B-A warm interval, which agrees with models of ocean heat convection. If a strong AMOC and high

NADW formation caused a warm climate, then shutting down the THC would cause a cool one. Weaver et al. (2003) find that B-A warm interval caused melting major northern hemisphere ice sheets, the Laurentide and Fennoscandian ice sheets, causing the YD, by shutdown of the AMOC. They found that MWP-1A and B-A warming interval are synchronous, and they placed the source of MWP-1A in the Antarctic. NADW formation is in an "off" mode after H1, providing a high in ice sheet thickness and extension, and a low in sea level. Then, warming of the southern hemisphere ~19,000 yr B.P. occurred when cooling of the North Atlantic caused the redistribution of global heat towards the southern hemisphere, in an effect known as bipolar seesaw (Broecker, 1998). The warming led to a partial collapse of the Antarctic Ice Sheet and MWP-1A. The flux of freshwater from MWP-1A in the Antarctic disrupts Antarctic deep water formation, leading to an increase in NADW that warms climate to levels of the B-A interval at 14,600 yrs B.P. (Weaver et al., 2003). Increased NADW formation causes the melting of Northern Hemisphere ice sheets as climate continues to warm, leading to the YD when the retreat of the LIS caused the collapse of proglacial Lake Aggassiz (Carlson et. al., 2007). The climate cools, sea level rise slows dramatically to 3 mm/year, and rerouting allows for the THC to strengthen, marking the end of the YD. Sea level rises at 11 mm/year through the end of deglaciation, bringing the planet to modern day sea levels.

The sequence of events from the BA warm interval to MWP 1-A and the YD has similar climate signals to DO cycles, indicating a plausible mechanism for DO events (Broecker, 1994). The observable geologic record shows that the BA warm interval led to MWP 1-A by the collapse of proglacial Lake Agassiz, shutting off THC and creating the YD cool period. The processes of these events remain observable in the field because glacial advance has not erased their erosional-depositional signature. Simultaneously, they emit a signal in paleoclimate proxy records while, making them useful in understanding the physical processes of abrupt climate change in the context of the paleoclimate records. As a potential analog, the warming of the BA warm interval compares to a warm DO event causing glacial retreat, MWP 1-A represents a freshwater routing event that turns off THC, and the YD represents the descent back into glacial conditions following a DO event. Therefore, a mechanism for abrupt climate change analogous to the events of the last deglaciation provides a logical framework for developing hypotheses for mechanisms of abrupt climate change. One such hypothesis that draws from the events of the last deglaciation is the freshwater routing hypothesis. As mentioned, the freshwater routing hypothesis proposes that changes in THC via routing of glacial meltwater cause abrupt climate change, similar to MWP 1-A affecting THC and causing the YD. This reports tests the freshwater routing hypothesis.

Freshwater Routing and the Climate System

In the wake of the Greenland ice core discoveries, the freshwater routing hypothesis was proposed as a mechanism to explain abrupt climate change in the North Atlantic during the last glacial period. The idea that changes in freshwater water routing patterns disrupted Atlantic thermohaline circulation gain popularity (e.g. Clark et al 2001; Bond et al. 1993; McManus et al 1994). The THC operates as a mechanism to distribute heat around the globe, which receives uneven distribution from the sun due to the earth's spherical geometry (Alley, 2000) (Figure 10).

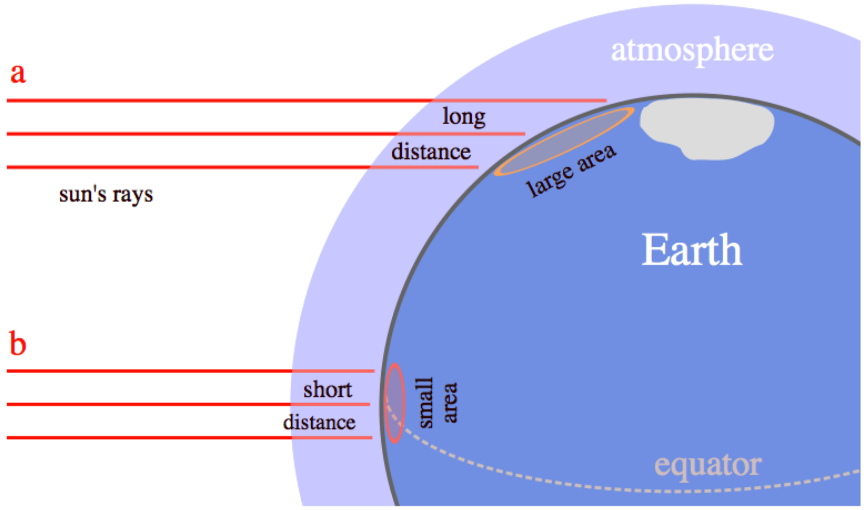

Figure 10. Schematic representation of how solar radiation has different concentrations at different latitudes, creating a temperature gradient and regional climates. The relationship exists due to the spherical geometry of the earth (Halasz).

Due to the curvature of the earth, the equator receives more sunlight per unit of area than at the equator. Higher latitudes received less "concentrated" radiation from the sun, because of how parallel rays have to spread out over a greater area, causing the equator to have a warmer climate than the poles.

The climate system seeks to distribute heat because of thermodynamics, where the temperature gradient between warmer oceans at the equator and colder water at the poles causes the fluid to flow. The surficial gradient between warm water at the surface that receives solar radiation and cold, dark water at the bottom of the ocean creates a 3-dimensional convection system (Figure 11). Warm water flows at the surface, and cold water flows along the ocean floor. In the Atlantic Ocean, as water travels north from the equator, heat gradually dissipates, while evaporation enriches the ocean in salt. As salinity increases, water density increases, which affects vertical convection. After traveling northward from the tropics, ocean water reaches a critical density due to lowered temperatures and increased salinity, causing downwelling as part of NADW formation near Iceland and Greenland (Clark et al., 2002). In the southern hemisphere, deep-water formation occurs at the Weddell and Ross Seas, where intense evaporation or brine rejection produces dense water that sinks along the continental slope

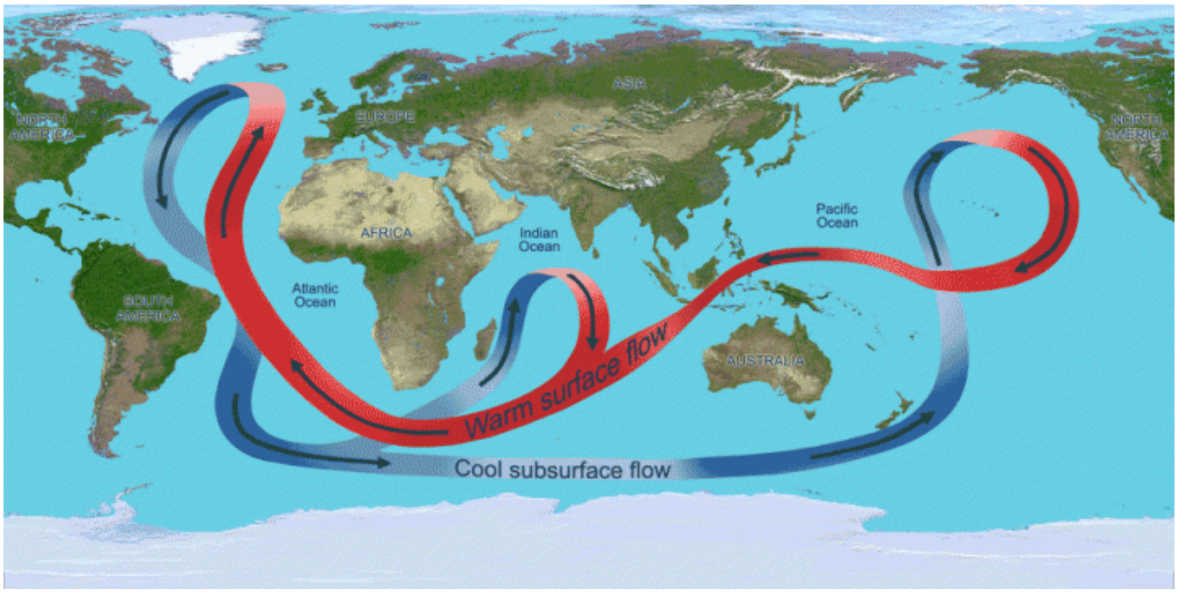

Figure 11. Graphic representation of the thermohaline circulation. Note sinking point in the North Atlantic. (NASA).

(Killworth 1983). According to the freshwater routing hypothesis, if freshwater runoff flows into the density-sensitive North Atlantic region of the thermohaline circulation, it will prevent NADW formation, effectively "turning off" THC.

Clark et al. (2001) provides a mechanism for changing freshwater runoff patterns on the North American continent during the last glacial period (Figure 12a). At maximum size of the Laurentide Ice Sheet (LIS) (Margin 1), freshwater flowed through the Mississippi River and into the Gulf of Mexico, allowing for the development of vigorous THC. However, when the LIS was at intermediate sizes (Margin 2), freshwater flowed through the Hudson River or the St. Lawrence River, running into the Atlantic at sensitive locations of NADW formation. The freshwater disrupted AMOC enough to shut it off and cause a cooling phase in a DO cycle.

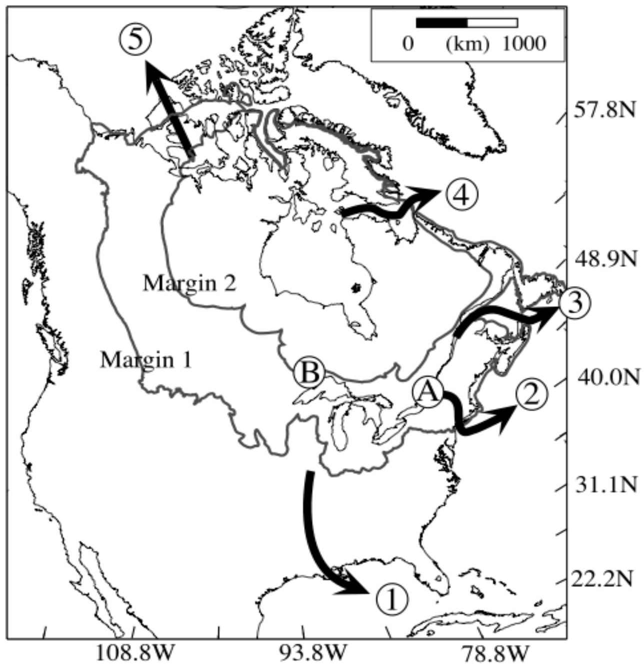

Figure 12a. Map depicting maximum and intermediate sizes of the LIS on the North American Continent. Maximum size is at Margin 1, where freshwater drains southward down the Mississippi River to the Gulf of Mexico. Intermediate size is at Margin 2, where freshwater drains eastward down the Hudson or St. Lawrence Rivers and shuts down the thermohaline circulation (Clark et al. 2001).

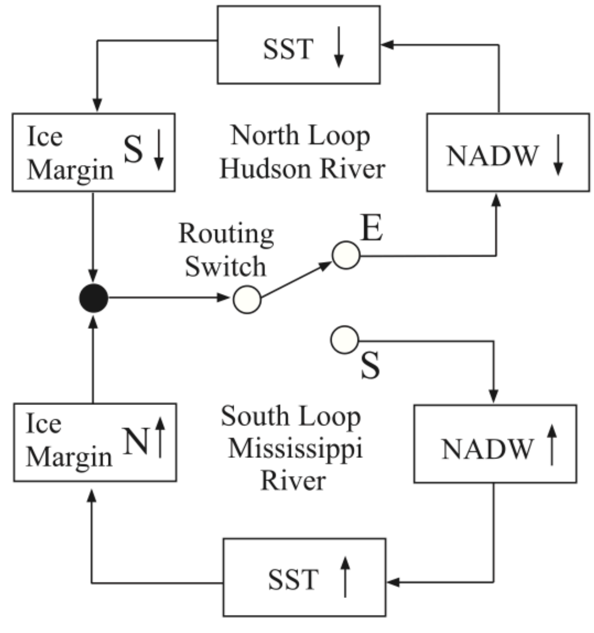

Figure 12b. Schematic representation highlighting the oscillatory nature of the freshwater routing hypothesis. It exhibits two loops that depend on the direction of freshwater routing. When freshwater routes to the south out of the Mississippi River, thermohaline circulation increases (NADW ↑, SST ↑), causing warming and the retreat of the ice margin northward. When freshwater routes to the east out of the Hudson and St. Lawrence Rivers, thermohaline circulation decreases (NADW ↓, SST ↓), causing cooling and the advance of the glacier southward. The two loops oscillate as part of a negative feedback loop (Clark et al. 2001).

The hypothesis suggests that these two processes oscillated back and forth numerous times over the course of the last glaciation period (Figure 12b). When thermohaline circulation increased, it caused the climate to warm and the LIS to retreat. When thermohaline circulation decreased, it caused the climate to cool and the LIS to advance, representing a negative feedback loop (Clark et al. 2001).

THC exists in multiple "modes" of operation, where each mode correlates to a different climatic response. The three modes of thermohaline circulation have different deep-water patterns (Figure 13). The three modes are labeled the stadial mode (cold), where NADW forms south of Iceland in the subpolar open North Atlantic, the interstadial mode (warm), where NADW forms in the Nordic seas, and the Heinrich mode (off), where NADW ceases and waters of Antarctic origin fills the Atlantic basin (Rahmstorf, 2002).

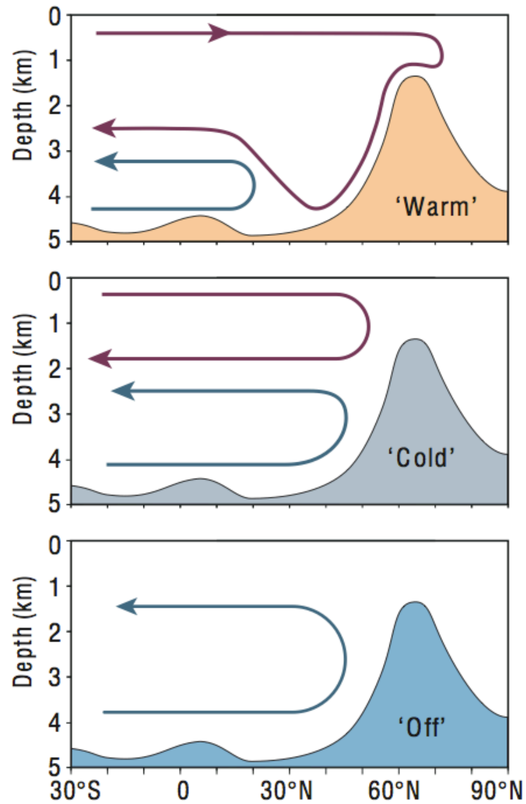

Figure 13. Schematic representation of the three modes of ocean circulation. Bottom axis represents cross-section of North Atlantic. Topography rise symbolizes the shallow sill between Greenland and Scotland. North Atlantic overturning is shown by the red line, Antarctic bottom water by the blue line. (Rahmstorf, 2002).

Alternate Mechanisms of Abrupt Climate Change

The freshwater routing hypothesis is merely one hypothesis for abrupt climate change, and alternative mechanisms to THC and glacial meltwater routing have been proposed. Wunsch (2006) provides a dissenting position to the significance of fluctuations in THC and freshwater routing to DO events. He argues that DO events have not yet been proven to be global; he posits that wind currents on an ice sheet can create the observed climate fluctuations on the short time scale; he points out that DO events ceased only when the LIS and the Fennoscandian Ice Sheet melted, supporting the role of wind currents and subsequent ocean waves in abrupt climate changes; he argues that the notion of THC turning on and off by freshwater input is unlikely to be correct for a variety of reasons because the wind field is the primary mechanism for changing the ocean current (Wunsch, 2006). Ultimately, Wunsch insists that in the face of ambiguous evidence, the scientific community should evaluate multiple hypotheses for abrupt climate change.

Heeding the calls of Wunsch (2006) and in the face of scant geologic evidence to support a simple freshwater routing model for DO events as proposed by Clark et al. (2001), alternate mechanisms have been proposed for abrupt climate change. The evidence for the role of freshwater routing and the THC in abrupt climate change exists for the YD, but applying it to DO events lacks support, and it may not be as simple as initially proposed (Carlson et al., 2007). Clement and Petersen (2008) argue that it is a major assumption that DO cycles, Heinrich events, and the YD are linked by fluxes in THC alone, and that abrupt climate change is more plausible as a product of feedbacks between freshwater routing, sea ice growth and retreat, tropical mechanisms, and THC. In particular, the influence of sea surface temperature (SST) on ice shelves has gained traction as a mechanism for abrupt climate events (e.g. Petersen et al., 2013; Marcott et al., 2011; Broecker et al., 2006; Li et al. 2005; Li et al. 2010). Marcott et al. (2011) identifies a new trigger for Heinrich events. They use benthic foraminifera to find that basin-wide subsurface warmings occurred in the North Atlantic as a response to a reduction in the AMOC. Their records indicate that Heinrich events occur when AMOC hits its lowest value, and subsurface temperatures reach their highest values, causing basalt melt under the ice shelf and culminating in the collapse of the ice-shelf. The ice shelf no longer holds back the ice-sheet and an ice-stream surge occurs, producing the armada of icebergs that eventually deposit the iconic IRD of Heinrich events. Applying a similar understanding of how subsurface warming leads to the collapse of ice shelves, Petersen et al. (2013) propose a new mechanism for DO cycles, where sea ice retreat and ice shelf growth set the timescales of DO cycles. Although substantial changes in AMOC occurred during DO stadials associated with Heinrich events, no such changes in AMOC are seen during non-Heinrich stadials (Shackleton, 2000). Therefore, large changes in AMOC cannot be the primary mechanism for *all* DO cycles. Instead, they develop a model for DO cycles controlled by sea-ice flux for fast changes and ice-shelf growth for slow changes (Figure 14).

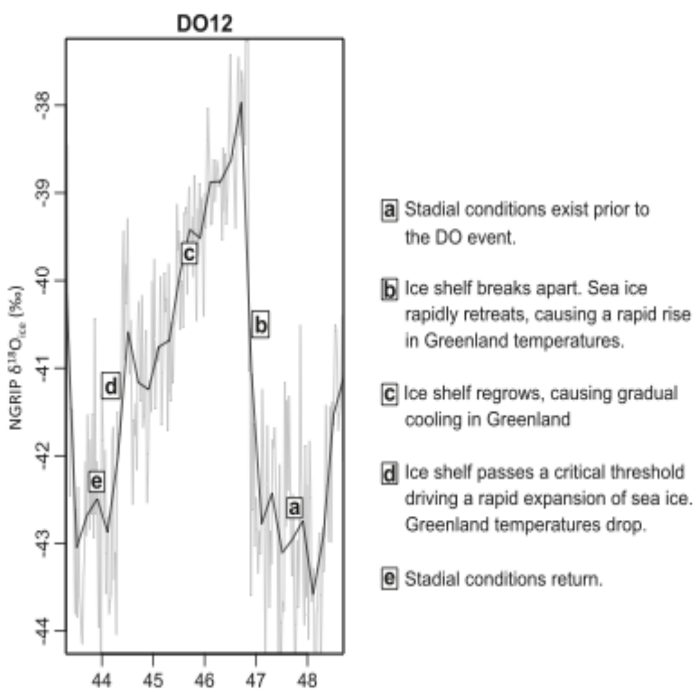

Figure 14. Representation of how new model for DO cycle behaves over time with respect to NGRIP $\delta^{18}O_{Ice}$ (Petersen et al. 2013).

The model begins during stadial conditions, where a large ice shelf and extensive sea ice cover causes regionally cold temperatures due to the effects of insulation and local albedo [a] (Li et al., 2010). The conditions would remain cold until subsurface warm waters destabilize the ice shelf and cause it to collapse, leaving sea ice and floating icebergs, which can quickly melt and increase the open-ocean area in a short period of time, creating abrupt warming—a DO event (beginning of a new DO cycle) [b]. During the ensuing interstadials phase, accumulation over the Greenland Ice Sheet increases due to the warmer temperatures and increased precipitation, causing the slow growth of a new ice shelf [c]. Temperature slowly cools as the ice shelf grows, but once the ice shelf reaches a threshold for sea-ice albedo feedback, sea ice will rapidly expand [d], rapidly returning climate to stadial conditions [e] (Petersen et al., 2013). The model combines the sea-ice mechanism of Li et al. (2010) with the ice-shelf collapse mechanism, creating a new mechanism for DO cycles that accounts for their distinct pattern of abrupt warming, slow cooling, followed by abrupt cooling back to stadial conditons.

Freshwater Forcing and Abrupt Climate Change in the 21st Century

The study of abrupt climate change via fluctuations in THC raises questions about whether or not we will face an abrupt climate change event during the 21st century. Computer models have been run to simulate maximum rates of melting of the Greenland Ice Sheet and its impact on AMOC, finding it unlikely that a shutdown will occur before 2100 (Stouffer et al., 2006; Clark et al. 2008). However, Rahmstorf et al. (2015) gives evidence to support that we may we have underestimated the likelihood of AMOC shutdown. Of note, the only region in the world to have cooled over the past century is at the site of NADW formation in the North Atlantic (Rahmstorf et al., 2015). This indicates a reduction in the strength of the AMOC, but prior estimates cite a probability of less than 10% for hitting the threshold for complete collapse by 2100 (IPCC, 2014). Rahmstorf et al. (2015) find that the AMOC is closer to its threshold than previously thought, and suggests that the IPCC probability is an underestimate. They also note that a shutdown in AMOC would not be completely catastrophic, although it would exacerbate problems of rising sea level and shifting weather patterns. Studies of abrupt climate change are societally relevant so that questions about our future can be answered, and warrants further research.

Foraminifera $\delta^{18}O$

Oxygen isotope ratios are useful as paleoclimate indicators in carbonate minerals because of the thermodynamic fractionation that occurs during precipitation (Urey, 1947). The equation for $\delta^{18}O$ is $\delta^{18}O= \{[(^{18}O/^{16}O)_{Sample}/(^{18}O/^{16}O)_{SMOW}] - 1\} \times 1000$ expressed in permil, where SMOW represents standard mean ocean water (Sharp, 2006). In addition to temperature, $\delta^{18}O$ in carbonate solids reflects salinity as a function of how seawater responds to changes in evaporation and precipitation (Lea, 2003). As observed in the process of Rayleigh Fractionation, evaporation of water prefers the lighter isotope ^{16}O. The removal of ^{16}O from oceans as water evaporates increases $\delta^{18}O_{Seawater}$ at the site of evaporation as the remaining water becomes enriched in ^{18}O. Additionally, evaporation leaves salt behind, which increases the salinity of the oceans in regions experiencing evaporation. The ocean water that has experienced substantial evaporation is a) saltier and b) enriched in ^{18}O, creating the correlation between salinity and $\delta^{18}O_{Seawater}$. Salinity itself does not affect the way in which foraminifera record $\delta^{18}O_{Seawater,}$ as fractionation between carbonates and water is not affected by this process. Similarly, regions that experience high precipitation exhibit decreases in $\delta^{18}O_{Seawater}$, as meteoric water has low $\delta^{18}O$ values. The degree of $\delta^{18}O_{Seawater}$ response to freshening depends upon the type of meteoric water entering the system. For example, glacial meltwater exhibits a very low $\delta^{18}O$ value of ~-30‰, while rivers typically exhibit ~-5‰ (Sharp, 2006). Also, oxygen isotopic ratios in foraminifera differ by species as a product of how temperature and salinity differ at the bottom of the ocean from the top of the ocean. For example, surficial plankton will record a different $\delta^{18}O$ signal than benthic plankton (Lea, 2003). To get a consistent reading of $\delta^{18}O$, it is important to use one species.

Foraminifera Mg/Ca

Elderfield and Ganssen (2000) demonstrated that variation in Mg/Ca with temperature exists in multiple species of plankton, including G. *bulloides,* and accurately represents variations in temperature due to partitioning of Mg during calcification. They pioneered research combining Mg/Ca paleotemperatures with oxygen isotope ratios, establishing its usefulness in probing past ocean-climate interactions. Hill et al. (2006) apply the methods of $\delta^{18}O$ and Mg/Ca to create a record of paleosalinity. They reason that given a record of temperature and salinity from $\delta^{18}O$ and a record of temperature from Mg/Ca, it is possible to reduce the record to purely salinity. The Mg/Ca temperature record serves as a record of temperature, and $\delta^{18}O$ records temperature *and* salinity. Therefore, if the two records are combined, the temperature record can effectively be pulled out of the $\delta^{18}O$ signal, leaving behind a salinity signal (Rahmstorf, 2002). Hill et al. (2006) recognized the particular usefulness of this method in evaluating freshwater fluxes, and applied it to testing the freshwater routing hypothesis. They created a record of paleosalinity for a core in the Gulf of Mexico (near the mouth of the Mississippi River; Route 1 in Fig. 12a) and compared salinity with the record of abrupt climate changes as recorded by $\delta^{18}O$ in GISP2 (Figure 15).

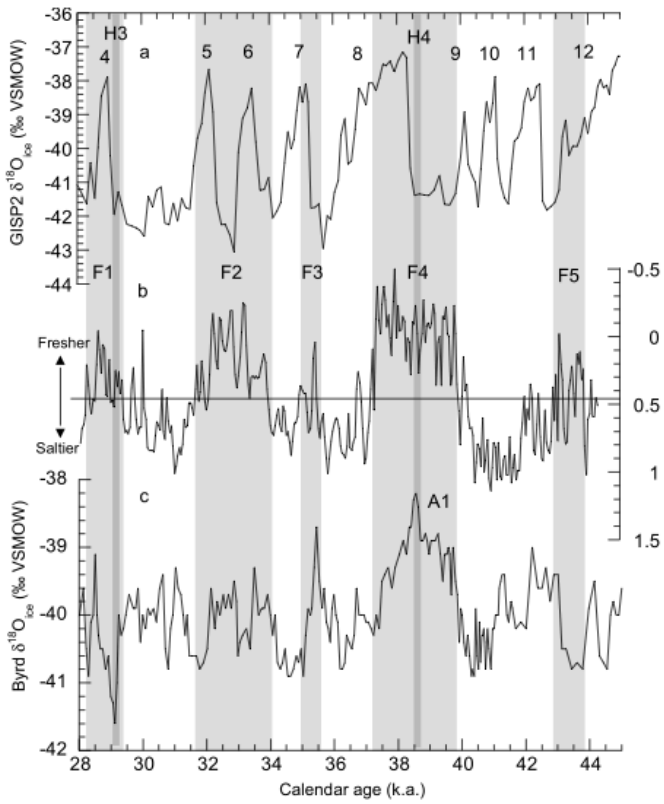

Figure 15. Comparison of paleosalinity (b) to δ^{18}O from GISP2 (a), a proxy for paleotemperature. Both are plotted against calendar age. Mean value indicated by horizontal bar. Numbers refer to Greenland interstadials. Light grey bars represent and the letter F (numbered 1-5) indicate freshwater events. Dark grey bars and letter H indicate Heinrich events. (C) represents Antarctic d^{18}O record. (Hill et al., 2006).

The results from Hill et al. (2006) indicate no consistent relationship between freshwater in the Gulf of Mexico and Greenland interstadials, opposing the freshwater routing hypothesis. The DO events (interstadials 4-12 in Fig. 13) do not align with changes in salinity as predicted by the hypothesis, preventing the association between changes in NADW formation and southward routing of meltwater from the LIS. Interestingly, the meltwater record exhibits close similarities with the ice core record of Antarctic climate. Although the conclusions challenge the freshwater routing hypothesis, they represent only one study, and more data is needed to further assess the hypothesis. The experiment in this report intentionally follows the same methodology as Hill et al. (2006) in order to provide a similar data set in a different region. This report uses a core near the Hudson River to evaluate Route 2 (Fig. 11a). It includes a record of paleosalinity compared to the GISP2 paleotemperature record in order to assess whether there is a correlation between freshwater influx and abrupt climate changes in the North Atlantic.

This experiment's data is expected to yield one of three distinct signals, providing paleoclimate information. In the first scenario, the Mg/Ca ratios (proxy of paleotemperature) perfectly follow along the $\delta^{18}O$ signal. The data would indicate that salinity near the mouth of the Hudson River exhibited very little variation in salinity during the period of the last glaciation between 40,000-30,000 ka BP. A possible interpretation would be that Hudson River freshwater did not change very much over this period of time, indicating that the LIS remained in Canada and did not drain into the Hudson River at all In the second scenario, salinity decreases (i.e. freshwater increases) at the same time as abrupt climate change events, D/O events and/or Heinrich events. The results then support the freshwater routing hypothesis, in that freshwater runoff disrupted the thermohaline circulation and caused abrupt climate change. If there is no correlation between changes in salinity and abrupt climate change events, then the results do not support the hypothesis.

Geologic and Paleoclimatic Setting

The sediment core studied in this experiment lies at 39° 13.5214′ N, 72° 16.5461′ W (Austin et al., 1998) located on the continental slope of the North American Plate, south of the mouth of the Hudson River (Figure 16). It is part of Ocean Drilling Program Log 174A, site 1073.

Figure 16. Satellite map depicting location of core on the continental slope in relation to the mouth of the Hudson River (Google Earth).

Sedimentology data has been drawn from Austin et al. (1998), which catalogued ODP 174A Site 1073. The sediment studied is from the Holocene through the late Pleistocene, and is largely dominated by mud. Foraminifer samples were taken from core depths ranging from 30m to 70m. The studied depths are from the middle part of Subunit 1A (interval 174A 1073A-4H-5, 48 cm, to 10H-2, 115cm). Here, sediment consists of clay and silty clay. The sediments are gray to dark gray, micaceous, and contain fine sand and silt laminae. The dominant mineralogy is quartz, feldspar, and calcite. There are thinly to thickly interbedded silty clays and sandy clays. The core displays thorough bioturbation and hydrotroilite staining. Soft sediment deformation appears in the form of slump folds, though these are relatively small (<10cm) in the span of a 40m sampling for this experiment.

The paleoclimatic setting of Site 1073 is lesser known, and is what this thesis seeks to gain more knowledge of. The GISP2 records and the known locations of the LIS inform current knowledge of the paleoclimate at the site during the Last Glacial Maximum (LGM). The LGM left a geomorphological record of erosion and deposition providing information about the retreat of glaciers from their maximum extent, but also erased any existing sedimentological features from earlier glaciers during the time of this research. The GISP2 records display large climatic swings throughout the last glaciation in Greenland (Alley, 2003). Evidence of climate changes in other parts of the world exhibit the same timing as D/O events, leading to the hypothesis that the climate on the Greenland Ice Sheet reflects the greater climate in the region, if not the Northern Hemisphere (Broecker, 1994). Due to the proximity of the Hudson River to the Greenland Ice Sheet, it is therefore reasonable to believe that the paleoclimate record produced by GISP2 reflects the paleoclimatic setting of Site 1073. Information about the location of glaciers prior to the LGM are not readily available, but it is reasonable to assume that the LIS existed around the latitude of the Hudson River during the study time period (42,000-28,000 ka) (Clark et. al, 2001; Alley, 2000).

CHAPTER 3 – METHODS

Samples from site 1073 were ordered from the Integrated Ocean Drilling Program core repository at University of Bremen, Germany, where the core is stored. The sediment was cored in July of 1997, and kept under freezing conditions in Germany since. Prior to this study, 13 radiocarbon dates had been processed from foraminifera by Beta Analytic (FL), each from a different depth, providing an age model for the core. An age-depth relationship was determined by fitting a line to the radiocarbon dates with an error of ±200 years. Samples were ordered to represent the period of time spanning from 42,000 yr BP to 28,000 yr BP (~40m-80m core depth). A 2-cm sample was selected every 40 cm (83 samples total), from depths 4H-7, 80-82 cm through 9H-4, 140-142 cm. Prior data (unpublished) existed for $\delta^{18}O$ from foraminifera for a span of 10m within the age range of this study. All procedures were the same for the previously processed data.

The sediment samples underwent a multi-step process in order to isolate foraminifera of the desired size. Each sediment sample was heated to 45 °C to remove moisture and increase the speed of sieving. The samples were individually placed into glass beakers with distilled water, and shaken on an electric shaking machine until all the sediment clumps were broken down. Then, each sample was wet sieved through a 63um mesh, with the assistance of tap water. The remaining sediments (>63um) were left to dry, and then placed into individual, labeled vials. Then, the sediment was dry sieved to isolate particles of size 250-355um. Using a microscope and a very fine wet paintbrush, calcite shells of the species *Globigerina bulloides* were removed from the surrounding sediment. *G. bulloides* plankton were chosen for the experiment because they live at the surface of the ocean, and their shells reflect the geochemistry of the environment. The surface is the desired study environment because if freshwater influxes occurred, they would be less dense and have an impact in the salinity of water at the surface. For $\delta^{18}O$ analysis, the majority of samples contained 10 forams that were averaged together to produce a single data point. However, some data points contain <10 forams. The forams were run through a sonicator two times, each with fresh distilled water, to remove excess fine sediments that may have be on the forams. The measuring of isotopic ratios of the foraminifera was completed at Lamont-Doherty Earth Observatory (Columbia University, NY) by Wei Huang. Isotopic analysis of the ratio of magnesium to calcium (Mg/Ca) in calcite shells of forams was also completed. The majority of the Mg/Ca data points contained at least 30 forams, with some data points using no less than 20 forams. These samples were subject to intense cleaning at Lamont-Doherty Earth Observatory, followed the contemporary methods for Mg/Ca processing. Using the methods previously discussed (Hill et al., 2006; Elderfield and Ganssen, 2000; Sharp, 2007) in section "Mg/Ca Analysis" of Chapter 2, salinity was isolated and compared to records of Greenland climate from GISP2 project.

CHAPTER 4 – RESULTS

Two graphs were created. The first is a running mean of $\delta^{18}O$ at Site 1073 plotted against calendar age, compared to GISP2 $\delta^{18}O$ values (Fig. 17).

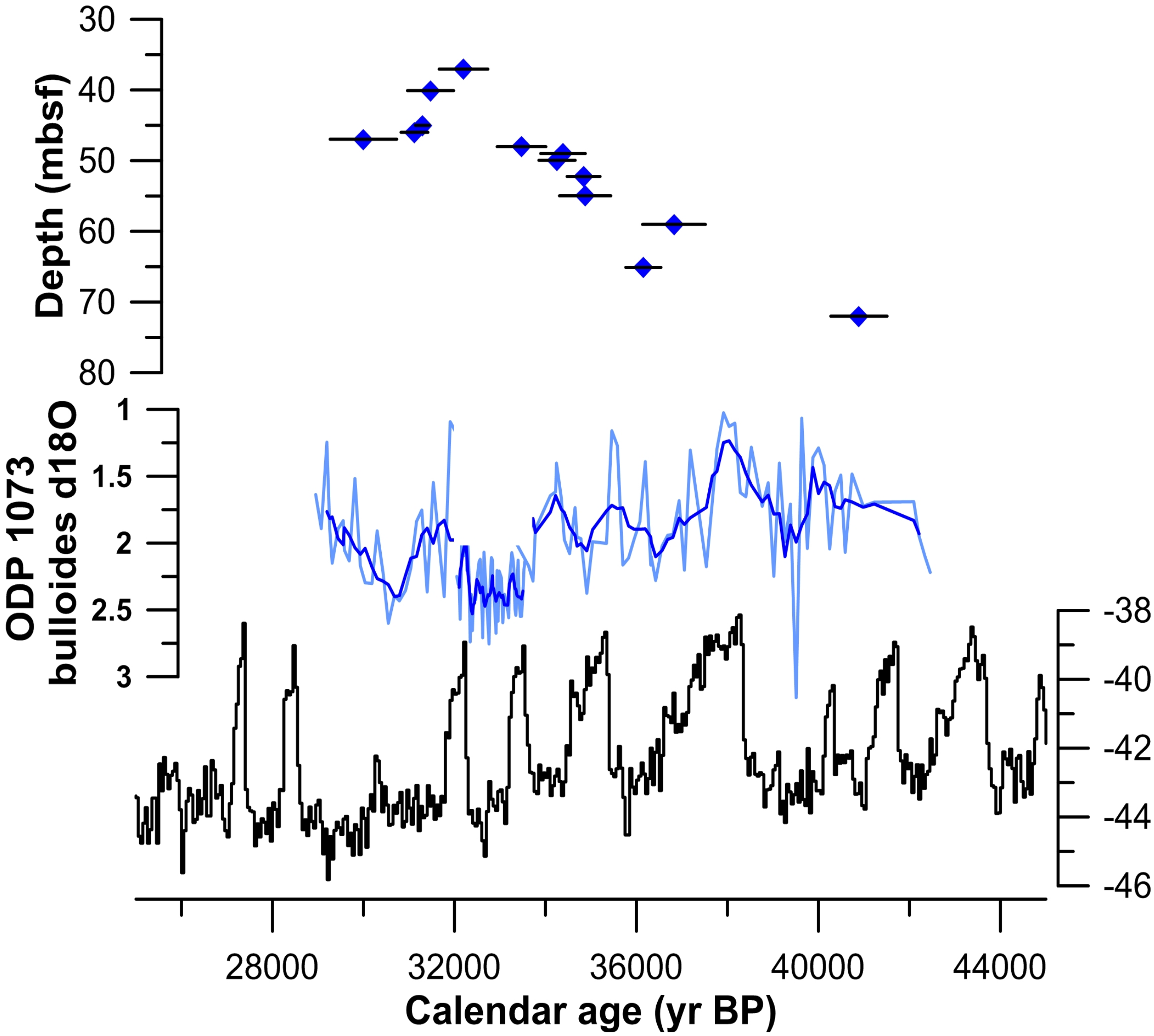

Figure 17. Graph of $\delta^{18}O$ vs. calendar age of G. bulloides at ODP 174 Site 1073A (dark blue represents running mean; light blue represents actual data). $\delta^{18}O$ from study site above the $\delta^{18}O$ record from GISP2 for comparison. Note that the scale for $\delta^{18}O$ of ODP 1073 is inverted from the scale for GISP2. Calendar age of foraminifera calculated by an average age relationship (linear) of radiocarbon dates taken at various depths. Time-scale for $\delta^{18}O$ of site 1073 subject to variation within ±200 year error.

The data indicate no clear trend between $\delta^{18}O$ from ODP 1073 and $\delta^{18}O$ from GISP2. Overall, the plot exhibits substantial noise. There is a maximum in the running mean of ODP 1073 near the year 38,000 BP. The maximum roughly parallels a local maximum in the GISP2 record, which has been documented as Heinrich event 4. Near the apparent near age 32,000 yr BP, there is a reversal in the age model. Analysis of the core reveals that there is no significant stratigraphic reversal to account for the reversal in radiocarbon age. The resolution of the data increases substantially for the calendar years ~35,000-32,000 yr BP, as samples were measured every 7 cm instead of every 40 cm for that corresponding depth interval.

The second graph is a plot of $\delta^{18}O$ adjusted for the temperature signal from Mg/Ca to represent isolated sea surface salinity ($\delta^{18}O_{Sal}$) against calendar age, compared to GISP2 $\delta^{18}O$ values and the Hill et al. (2006) data (Figure 18). There are few data points for $\delta^{18}O_{Sal}$ in comparison with $\delta^{18}O$. There were low quantities of individual foraminifers in the 2 cm samples, limiting the quantity of Mg/Ca data, as the analysis requires ~40 forams. Similar to Fig. 14, Fig. 15 lacks clear trends. The signal is fairly flat, barring a spike at the maximum $\delta^{18}O_{Sal}$ value near 34,000 yr BP. The maximum is substantially higher than the other values, but is created by only two data points. Some aluminum was recorded in a few samples, representing possible contamination by allogenic sediment.

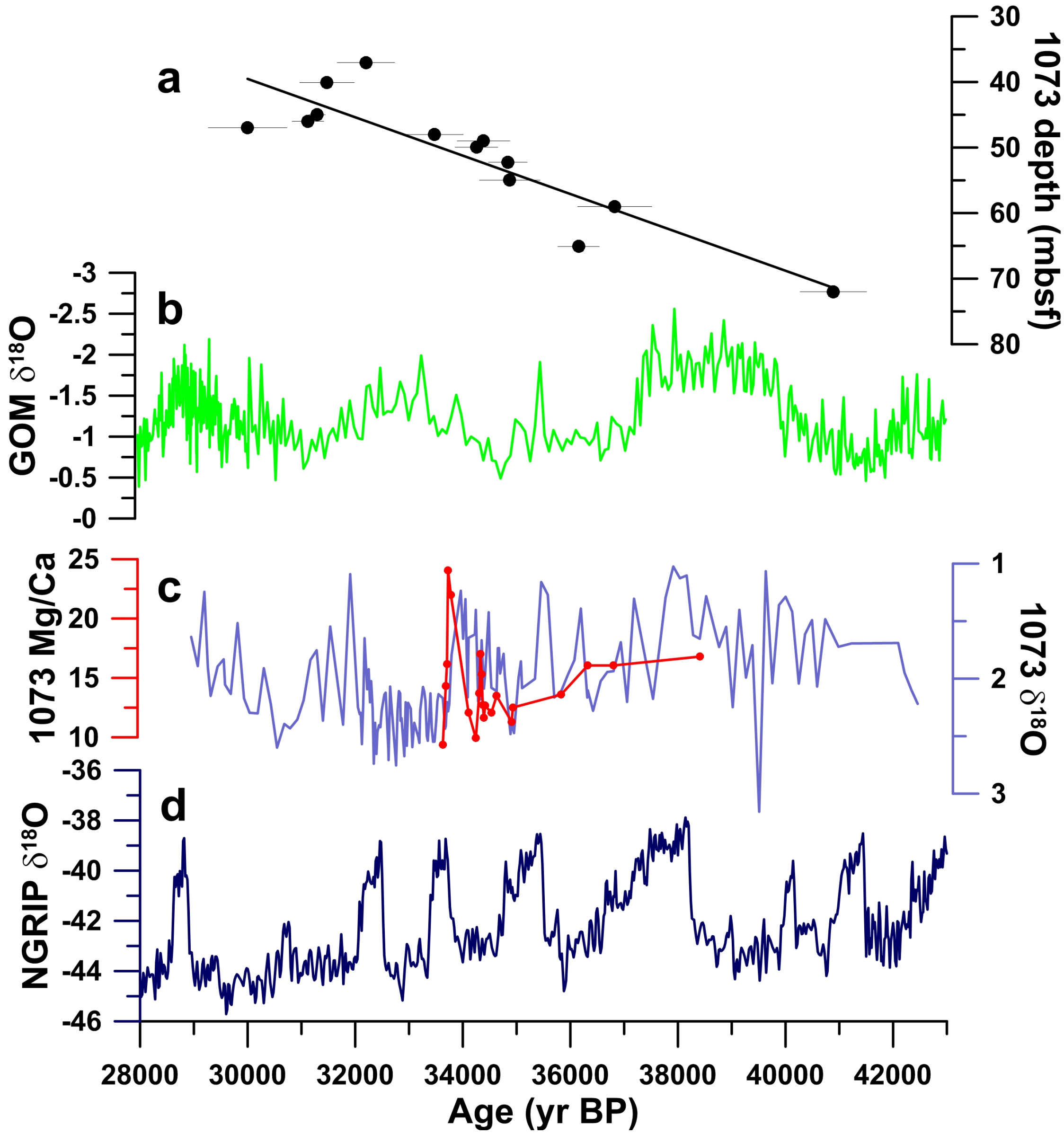

Figure 18. $\delta^{18}O_{Sal}$, GISP2 $\delta^{18}O$ record, Site 1073A $\delta^{18}O$ record, and Hill et al. (2006) $\delta^{18}O_{GOM}$ data against age model. Calendar age and $\delta^{18}O$ are the same as in Fig. 14, see caption for Figure 14. $\delta^{18}O_{Sal}$ overlays $\delta^{18}O$ and serves as a proxy for salinity, ultimately representing Hudson River paleodischarge record.

CHAPTER 5 – DISCUSSION

Interpretation of Hudson River Paleodischarge Record

The lack of apparent trends between $\delta^{18}O$ at site 1073A and $\delta^{18}O$ at GISP2 provides weak evidence to support or deny the freshwater routing hypothesis. The challenges in making meaningful interpretations of the data lie in its noise and its resolution. The noise is observed in how data points from adjacent samples exhibit back and forth fluctuations of up to 1.5‰ $\delta^{18}O$.. Analysis of the sediment core showed that substantial bioturbation had occurred in the sediment, which explains the noise. After foraminifera of a given age are deposited, benthic organisms move around in the sediment, mixing forams of different ages. In effect, each value represents an average of sea surface conditions from a wider time span it initially appears on the graph, reducing the confidence in an individual point to be representative of changes in sea surface water. The dataset also lacks distinguishable larger-scale trend. With high noise and without clear trends, the ±100 year error of the radiocarbon age is exacerbated. If a pattern were present, it would be possible to adjust the age model within error to such that $\delta^{18}O$ from 1073A matches $\delta^{18}O$ from GISP2, within error, knowing that for small age-model fluctuations it's reasonable to align with the points of abrupt temperature shifts and then stretch ice-core linearly until points align (Bond et al., 1993).

However, large-scale trends in a noisy $\delta^{18}O$ signal have merit. The running mean was used to mitigate the impact of noise in interpreting the data. Despite the running mean, the noise is substantial enough that the samples taken at 40cm resolution cannot be interpreted to be representative of trends in surface seawater conditions. The 10m section of core with samples every 7cm shows how varied the values for $\delta^{18}O$ can be over short depth intervals, which supports that a higher resolution is necessary for the entire study. In the higher resolution span of the core from ~35,000-32,000 yr BP, trends in running mean are more representative of sea surface conditions, but there is not enough core sampled at 7cm intervals to make meaningful conclusions between $\delta^{18}O$ at site 1073A and $\delta^{18}O$ of GISP2. Further research should sample sediment at 7cm intervals, creating a high-resolution $\delta^{18}O$ record over the 40m of studied core.

Similarly to the $\delta^{18}O$ results, the low quantity of $\delta^{18}O_{Sal}$ values prevents meaningful analysis of Hudson River paleodischarge. It was expected that if the locations of the LIS did control freshwater routing, that the changes in freshwater would be observable in $\delta^{18}O_{Sal}$. Without enough data points, it is not possible to sync up changes in $\delta^{18}O_{Sal}$ with DO events recorded in GISP2. Further research should include more Mg/Ca data, and at the 7cm resolution.

Conclusions

Further research is necessary in order to evaluate the freshwater routing hypothesis for abrupt climate change based on Hudson River paleodischarge. Higher resolution $\delta^{18}O$ is and more Mg/Ca data points are needed to make meaningful interpretations. However, the premise for analyzing the data remains valid. In light of discussions of alternate mechanisms for abrupt climate change, this test for Hudson River paleodischarge should not be abandoned. In order to continue to progress our understanding of abrupt climate change, scientists must test the existing ideas. This thesis provides a framework for more research into Hudson River paleodischarge. With more data, it becomes possible to assess the influence of glacial meltwater routing events on THC.

The ice core data has value beyond an academic interest in understanding the earth's climatic history because knowledge of abrupt climate change has societally relevant applications for how we should interact with the climate in the future. Furthermore, in the context of contemporary debates about the impacts of anthropogenic climate change, it’s imperative that we develop our scientific understanding of the climate feedbacks, thresholds, and globalizers that control the climate system.

REFERENCES CITED:

Andersen, K.K., Azuma, N., Barnola, J. M., Bigler, M., Biscaye, P., Caillon, N., Chappellaz, J., Clausen, H.B., Dahl-Jensen, D., Fischer, H., others, 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. Nature 431, 147–151.

Alley, R. B. 2000. *The Two-mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future*. Princeton, N.J.: Princeton University Press.

Alley, R. B., J. Marotzke, W. D. Nordhaus, J. T. Overpeck, D. M. Peteet, R. A. Pielke, R. T. Pierrehumbert, et al. 2003. "Abrupt Climate Change." *Science* 299 (5615): 2005–10. doi:10.1126/science.1081056.

Bond, G., H. Heinrich, W. Broecker, L. Labeyrie, J. Mcmanus, J. Andrews, S. Huon, et al. 1992. "Evidence for Massive Discharges of Icebergs into the North-Atlantic Ocean During the Last Glacial Period." *Nature* 360 (6401): 245–49. doi:10.1038/360245a0.

Bond, G., W. Broecker, S. Johnsen, J. Mcmanus, L. Labeyrie, J. Jouzel, and G. Bonani. 1993. "Correlations Between Climate Records from North-Atlantic Sediments and Greenland Ice." *Nature* 365 (6442): 143–47. doi:10.1038/365143a0.

Broecker, W.S., and G. H. Denton. 1989. "The Role of Ocean-Atmosphere Reorganizations in Glacial Cycles." *Geochimica Et Cosmochimica Acta* 53 (10): 2465–2501. doi:10.1016/0016-7037(89)90123-3.

Broecker, W. S. 1994. "Massive Iceberg Discharges as Triggers for Global Climate-Change." *Nature* 372 (6505): 421–24. doi:10.1038/372421a0.

Broecker, W.S., 1998. Paleocean circulation during the last deglaciation: a bipolar seesaw? Paleoceanography 13, 119–121.

Broecker, W. S. 2006. "Abrupt Climate Change Revisited." *Global and Planetary Change* 54 (3–4): 211–15. doi:10.1016/j.gloplacha.2006.06.019.

Broecker, W. S., G. H. Denton, R. L. Edwards, H. Cheng, R. B. Alley, and A. E. Putnam. 2010. "Putting the Younger Dryas Cold Event into Context." *Quaternary Science Reviews* 29 (9-10): 1078–81. doi:10.1016/j.quascirev.2010.02.019.

Carlson, A.E., P. U. Clark, B. A. Haley, G. P. Klinkhammer, K. Simmons, E. J. Brook, and K. J. Meissner. 2007. "Geochemical Proxies of North American Freshwater Routing during the Younger Dryas Cold Event." *Proceedings of the National Academy of Sciences of the United States of America* 104 (16): 6556–61. doi:10.1073/pnas.0611313104.

Clark, P. U., N. G. Pisias, T.F. Stocker, and A. J. Weaver. 2002. "The Role of the Thermohaline Circulation in Abrupt Climate Change." *Nature* 415 (6874): 863–69. doi:http://dx.doi.org.proxy.bc.edu/10.1038/5863a.

Clark, P.U., Marshall, S.J., Clarke, G.K., Hostetler, S.W., Licciardi, J.M., Teller, J.T., 2001. Freshwater forcing of abrupt climate change during the last glaciation. Science 293, 283–287.

Clement, A. C., and L. C. Peterson. 2008. "Mechanisms of Abrupt Climate Change of the Last Glacial Period." *Reviews of Geophysics* 46 (4): RG4002. doi:10.1029/2006RG000204.

Cook, J. 2014. "CO2 lags temperature." *Skeptical Science*. Web. 25 Apr. 2015.

Dansgaard, W., S. J. Johnsen, H. B. Clausen, D. Dahljensen, N. S. Gundestrup, C. Hammer, C. Hvidberg, et al. 1993. "Evidence for General Instability of Past Climate from a 250-Kyr Ice-Core Record." *Nature* 364 (6434): 218–20. doi:10.1038/364218a0.

Elderfield, H., and G. Ganssen. 2000. "Past Temperature and δ18O of Surface Ocean Waters Inferred from Foraminiferal Mg/Ca Ratios." *Nature* 405 (6785): 442–45. doi:10.1038/35013033.

Ganopolski, A., and S. Rahmstorf. 2002. "Abrupt Glacial Climate Changes due to Stochastic Resonance." *Physical Review Letters* 88 (3): 038501. doi:10.1103/PhysRevB.88.038501.

Hays, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. Science 194, 1121–1132. doi:10.1126/science.194.4270.1121

Heinrich, H. 1988. "Origin and Consequences of Cyclic Ice Rafting in the Northeast Atlantic-Ocean During the Past 130,000 Years." *Quaternary Research* 29 (2): 142–52. doi:10.1016/0033-5894(88)90057-9.

Hemming, S. R. 2004. "Heinrich Events: Massive Late Pleistocene Detritus Layers of the North Atlantic and Their Global Climate Imprint." *Reviews of Geophysics* 42 (1): RG1005. doi:10.1029/2003RG000128.

Hill, H. W., B.P. Flower, T. M. Quinn, D. J. Hollander, and T.P. Guilderson. 2006. "Laurentide Ice Sheet Meltwater and Abrupt Climate Change during the Last Glaciation." *Paleoceanography* 21 (1): PA1006. doi:10.1029/2005PA001186.

Johnson, R. G, and B. T. McClure. 1976. "Model for Northern Hemisphere Continental Ice Sheet Variation." *Quaternary Research* 6 (3): 325–53. doi:10.1016/0033-5894(67)90001-4.

Killworth, Pd. 1983. "Deep Convection in the World Ocean." *Reviews of Geophysics* 21 (1): 1–26. doi:10.1029/RG021i001p00001.

Lea, D.W. 2003. “Elemental and Isotopic Proxies of Past Ocean Temperatures.” *Treatise on Geochemistry* 6: 365–90.

Li, C., Battisti, D.S., Tziperman, E., Schrag, D.P., 2005. Abrupt Climate Shifts in Greenland Due to Displacements of the Sea Ice Edge.

Li, C., Battisti, D.S., Bitz, C.M., 2010. Can North Atlantic Sea Ice Anomalies Account for Dansgaard–Oeschger Climate Signals?*. J. Climate 23, 5457–5475. doi:10.1175/2010JCLI3409.1

MacAyeal, D.R., 1993. Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic’s Heinrich events. Paleoceanography 8, 775–784. doi:10.1029/93PA02200

Marcott, S. A., P. U. Clark, L. Padman, G. P. Klinkhammer, Scott R. Springer, Z. Liu, B. L. Otto-Bliesner, et al. 2011. “Ice-Shelf Collapse from Subsurface Warming as a Trigger for Heinrich Events.” *Proceedings of the National Academy of Sciences of the United States of America* 108 (33): 13415–19. doi:10.1073/pnas.1104772108.

McManus, J. F., R. Francois, J. M. Gherardi, L. D. Keigwin, and S. Brown-Leger. 2004. “Collapse and Rapid Resumption of Atlantic Meridional Circulation Linked to Deglacial Climate Changes.” *Nature* 428 (6985): 834–37. doi:10.1038/nature02494.

Meissner, K. J., and P. U. Clark. 2006. “Impact of Floods versus Routing Events on the Thermohaline Circulation.” *Geophysical Research Letters* 33 (15): L15704. doi:10.1029/2006GL026705.

Petersen, S. V., D. P. Schrag, and P. U. Clark. 2013. “A New Mechanism for Dansgaard-Oeschger Cycles.” *Paleoceanography* 28 (1). doi:10.1029/2012PA002364.

Rahmstorf, S. 2002. “Ocean Circulation and Climate during the Past 120,000 Years.” *Nature* 419 (6903): 207–14. doi:10.1038/nature01090.

Rahmstorf, S. 2003. “Timing of Abrupt Climate Change: A Precise Clock.” *Geophysical Research Letters* 30 (10): 1510. doi:10.1029/2003GL017115.

Rahmstorf, S., Box, J.E., Feulner, G., Mann, M.E., Robinson, A., Rutherford, S., Schaffernicht, E.J., 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Clim. Change 5, 475–480. doi:10.1038/nclimate2554

Rooth, C. 1982. “Hydrology and Ocean Circulation.” *Progress in Oceanography* 11 (2): 131–49. doi:10.1016/0079-6611(82)90006-4.

Shackleton, N.J., 2000. The 100,000-Year Ice-Age Cycle Identified and Found to Lag Temperature, Carbon Dioxide, and Orbital Eccentricity. Science 289, 1897–1902. doi:10.1126/science.289.5486.1897

Sharp, Z. 2007. *Principles of Stable Isotope Geochemistry*. Upper Saddle River, NJ: Pearson/Prentice Hall. Print.

Stouffer, R.J., Yin, J., Gregory, J.M., Dixon, K.W., Spelman, M.J., Hurlin, W., Weaver, A.J., Eby, M., Flato, G.M., Hasumi, H., others, 2006. Investigating the causes of the response of the thermohaline circulation to past and future climate changes. Journal of Climate 19, 1365–1387.

Urey, H.C. 1947. "The Thermodynamic Properties of Isotopic Substances." *Journal of the Chemical Society (Resumed)*, no. 0 (January): 562–81. doi:10.1039/JR9470000562.

Voelker, H.L., and Workshop Participants. 2002. "Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: a database. *Quaternary Science Reviews* 21: 1185–1212.

Weaver, A. J., O. A. Saenko, P. U. Clark, and J. X. Mitrovica. 2003. "Meltwater Pulse 1A from Antarctica as a Trigger of the Bølling-Allerød Warm Interval." *Science* 299 (5613): 1709–13. doi:10.1126/science.1081002.

Wunsch, C. 2006. "Abrupt Climate Change: An Alternative View." *Quaternary Research* 65 (2): 191–203. doi:10.1016/j.yqres.2005.10.006.