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Past and future ice age initiation: the role of an intrinsic deep-ocean millennial oscillation

R. G. Johnson

Department of Earth Sciences University of Minnesota, 310 Pillsbury Drive S.E., Minneapolis, MN 55455, USA

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Correspondence to: R. G. Johnson (glenjay@bitstream.net)

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Abstract

This paper offers three interdependent contributions to studies of climate variation: (1) the recognition and analysis of an intrinsic millennial oceanic oscillation that affects both Northern and Southern high latitude climates, (2) The recognition of an oceanographic switch to ice-free seas west of Greenland that explains the initiation of the Last Ice Age, and (3) an analysis of the effect of increasing salinity in the seas east of Greenland that suggests the possibility of the initiation of an ice age threshold climate in the near future. In the first contribution the millennial oscillation in the flow of the North Atlantic Drift reported by Bond et al. (1997) is proposed to be part of a 1500 yr intrinsic deep ocean oscillation. This oscillation involves the exchange of North Atlantic intermediate-level deep water (NADW) formed in the seas east of Greenland with Antarctic Bottom Water formed in a shallow-water zone at the edge of the Antarctic continent. The concept of NADW formation is already well known, with details of the sinking water flowing out of the Greenland Sea observed by Smethie et al. (2000) using chlorofluorocarbon tracers. The concept of Antarctic Bottom Water formation is also already well established. However, its modulation by the changing fraction of NADW in the Southern Ocean, which I infer from the analysis of Weyl (1968), has not been previously discussed. The modulated lower-salinity Antarctic Bottom Water that reaches the northern North Atlantic then provides negative feedback for the cyclic variation of NADW formation as proposed here. This causes the 1500 yr bipolar oscillation. The feedback suggests the possible sinusoidal character of the proposed oscillation model. The model is consistent with the cooling of the Little Ice Age (Lamb, 1972, 1995), and it also correctly predicts NASA's observation of today's record maximum area of winter sea ice on the Southern Ocean and the present observed record low rate of Antarctic Bottom Water production cited by Broecker (2000). The sinusoidal form of this conceptual model is therefore reinforced by both old and new data, and provides insights into world-wide climate change.

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The second contribution of this paper is a hypothesis for the initiation of Pleistocene ice ages, typified by the Last Ice Age that began 120 000 yr BP. Instead of the classical Northern high-latitude summer cooling caused by orbital precession and changes in Earth's axis inclination, this hypothesis proposes the sudden onset of year-round ice-free seas west of Greenland, with greatly increased precipitation in the ice sheet nucleation regions of Baffin Island, northern Quebec, and Labrador. Devon Island ice-core studies by Koerner at al. (1988) and deep-sea sediment data reported by Fillon (1985) support the concept of ice-free seas west of Greenland and imply the initial meteorological conditions that are proposed here. These conditions are consistent with the heavy precipitation inferred by Adkins et al. (1997) from deep-sea sediment data. The changes in northeastern Canada were accompanied by quite cold conditions in northern Europe, inferred by Field et al. (1994) from tree pollen data. The European cooling was probably caused by loss of the recurring Iceland low-pressure system due to the dominant effect of a frequent stronger low-pressure system over the Labrador Sea, as postulated in this paper. The key to ice-free seas west of Greenland is the loss of the near-surface stratification that normally enables sea ice to freeze. Using the high-resolution European Space Agency's ENVISAT system, I have monitored the flows through the Nares Strait and found that the dominant southward flow of lower density polar water into Baffin Bay correlated with the growing area of seasonal sea ice forming early in the winter in the Bay near the southern end of the Strait. This implies that low-salinity polar water was the cause of the stratification. A search for the cause of the stratification loss then became a search for the cause of the loss of the southward flow of polar water. The loss could have occurred if denser and more saline Atlantic water replaced the polar water in-flow. Medieval historical records suggest that an analogous partial replacement probably did occur during the early medieval climatic optimum, with some warmer Atlantic water removing the thick perennial sea ice along Greenland's north coast. The NADW formation rate and the Spitsbergen-Atlantic Current (SAC) flow were then near maximum values. I hypothesize that enough of the thick perennial sea ice along Greenland's north coast was removed by the penetration of the

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SAC flow into the polar ocean to enable a medieval voyage eastward along the coast in AD 1118. This voyage is implied by an old map record showing Greenland realistically as an island. An even stronger SAC flow associated with a stronger maximum in the 1500 yr intrinsic oscillation of the oceanic system was the likely trigger for the initial conditions of ice-sheet growth when the Last Ice Age began.

The third contribution of this paper is the hypothesis that modern society's activities might cause a repetition of the transition to an ice age threshold climate within one or two decades from 2013. This possibility depends on a continuing increase of salinity in the seas east of Greenland, with a corresponding increase of NADW formation and the SAC flow. The increase is currently being driven by the increasing rate of the saline Mediterranean outflow that contributes to the North Atlantic Drift. The rate increase is a consequence of the increasing salinity of the Mediterranean Sea as reported by European oceanographers (Science, 279, 483–484, 1998). The rising salinity of the Mediterranean and its increasing outflow is attributed to the diversion of nearly all the in-flowing rivers for irrigation. A further substantial salinity increase should occur with the loss of all perennial polar sea ice possibly within one or two decades from 2013 if the present trend of loss continues. The trend is displayed on the University of Illinois internet site: http://arctic.atmos.uiuc.edu/cryosphere/. The increasing salinity of the Greenland Sea is now reflected in an increasing northward winter penetration by the SAC flow. According to Lamb (1972), during the early 20th century at the time of maximum extension of sea ice in April, open water normally extended only as far north as the southern cape of Spitsbergen at about 76.6° N. But in Aprils of 2013 and 2014, open water extended 380 km farther northward to the north coast of Spitsbergen. When the SAC was running strongly to replace sinking NADW in February of 2014, I observed open water extending about 730 km north from the cape into the polar ocean to latitude 83° N, where the penetration of the SAC flow was beginning to obstruct the southward flow of polar water. Even greater seasonal extensions of the SAC flow are expected with an additional Greenland Sea salinity increase after the loss of all perennial polar sea ice. This could cut off southward movement of polar water through the

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Fram Strait during much of the winter, and send annual pulses of the denser Atlantic water of the SAC flow into the sea north of Greenland. If these annual pulses begin to occur and allow enough denser Atlantic water to flow southward through the Nares Strait, the Baffin Bay stratification would be lost and a switch to an ice age threshold would occur. The severity of the resulting cold regional climate might have a disruptive effect on higher-latitude societies.

1 Introduction

The last interglacial climate interval ended about 120 000 yr BP when new glaciation began in Canada after about 6000 yr of a warm and relatively stable climate. The present interglacial has now also lasted about 6000 yr, and the idea of an imminent renewal of ice sheet growth has occupied the attention of many workers in the climate field for almost a century. The suspected cause of the ending of the last interglacial was decreasing Northern Hemisphere summer insolation due to cyclic change of Earth's orbital parameters (Milankovitch insolation, Hays et al., 1976; Berger, 1978). This is widely assumed to have caused a cooling that initiated ice sheet growth. However, in an exhaustive study Rind et al. (1989) used the values of Milankovitch insolation in the general circulation model of the Goddard Institute for Space Studies and were unable to initiate glacial ice cover in Northern high-latitude regions. They concluded that: "If the model was correct … we really do not understand the cause of ice ages and the Milankovitch connection." This paper proposes a more subtle connection between ice age initiation and orbital change, and addresses the question: Why was the last ice age triggered so abruptly after about 6000 yr of quite ice-free Northern interglacial climate? And what does the proposed explanation imply for possible future climate change? In the concept proposed here, ice sheet growth was initiated by a change to a strong and persistent cyclonic circulation over northeastern Canada when the seas west of Greenland became ice-free. The result was a much larger moisture supply brought to the ice sheet nucleation areas under cloudy skies. The root cause for

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this was a critical point in the slowly increasing salinity of the Mediterranean Sea due to diminishing strength of African monsoons over the last interglacial. At that critical point, a minimum in the ~1500 yr-oscillation of lower-salinity Antarctic Bottom Water content in the North Atlantic was combined with the stronger saline Mediterranean outflow to increase the North Atlantic Drift salinity and flow to an unusually high level. The Drift supplies the saline surface water that largely determines the rate of NADW formation. Consequently an unusual maximum in salinity of the Drift implies a similar maximum in Drift flow needed to replace sinking NADW. Therefore the Drift is a key factor in the ice age initiation as well as an essential link in the deep-ocean oscillation (Fig. 1). The first indication of the ~1500 yr cycle in the Drift flow was found in the Holocene record of marine sediments and sand from deep-sea cores in the northeastern North Atlantic (Bond et al., 1997). Since then many efforts have been made to explain the cycles, often by invoking salinity variations caused by melt water discharges associated with Heinrich and Daansguard–Oeschger events and their seesaw effects on circulation in the North Atlantic and Southern Oceans. Among these are reports by Stocker (1998), Broecker (1998, 2000), Seidov et al. (2001), Seidov and Maslin (2001), and Rahmstorf (2002). However, since about 6000 yr BP when the last major Canadian glacial ice melted, significant melt water change has been absent. Nevertheless, millennial climate extremes have recently recurred in northern Atlantic regions, with debated causes. In particular there is not a consensus as to the cause of the climate extreme of the Little Ice Age around AD 1750. There is little doubt that this cold period was sometimes made colder by the atmospheric effects of occasional volcanic eruptions. Miller et al. (2012) argue that eruptions and associated feedback may be adequate to explain the Little Ice Age. Broecker (2000) suggested that it might have been initiated by a change in thermohaline circulation. Reduced intrinsic solar radiation has been proposed by some, in part because an anomalous period of quiet sun from AD 1680 to AD 1712 occurred near the time of coldest years in northern Europe and elsewhere (Lamb, 1972). But in northern North Atlantic regions the centuries-long persistence of climatic warmth during the earlier medieval climatic optimum and the climatic cold

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during the Little Ice Age probably reflect a long-term intrinsic oscillation in the flow of the North Atlantic Drift and its northward transport of heat. Hints of a deep-ocean oscillation mechanism are found in the literature. Broecker (2000) mentions a connection between Daansguard-Oeschger cycles of glacial times and a possible link to a seesaw of deep-water formation between the Atlantic and Southern Oceans. Reid's (1979) observations of high trace amounts of silica in water upwelling west of the British Isles imply an Antarctic Bottom Water connection. Weyl (1968) has described the influence of NADW in the Southern Ocean on the formation of Antarctic sea ice, a necessary link in the modulation of Antarctic Bottom Water formation. Although the fact of Antarctic Bottom Water formation is well known, the cause of its variation is not. This complex deep-ocean oscillation proposed here is of fundamental importance, and a model of the oscillation is discussed first. In the context of the model, the cause of the initiation of the last ice age in Canada becomes more clear, and leads to an explanation for the transitory ice-age threshold climate that began about 120 000 yr BP in northern Europe.

2 The intrinsic oscillation hypothesis

Mixing between different levels of the world's oceans occurs wherever there is sinking or upwelling. Superposed on this small scale mixing are two strong effects involving an exchange of deep-water masses (Fig. 1). In the northern North Atlantic, relatively saline water that is cooled in the winter sinks from the surface in the seas east of Greenland and mixes and equilibrates at the 2000–3500 m-depth to form NADW. Some of this water mass moves southward and mixes into the Southern Ocean (Weyl, 1968), and its presence enhances Antarctic Bottom Water formation. In the Southern Ocean, water made denser by salt rejection in the winter freezing process sinks into the deepest ocean at $\sim$4000 m-depth to form Antarctic Bottom Water. Some of this water mass reaches the northern North Atlantic and mixes up into the Drift where its low salinity inhibits NADW formation. Delays in transport and mixing enable the resulting oscillations of NADW concentration in the Southern ocean, the Antarctic Bottom Water

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concentration in the northern North Atlantic, and the variation in the North Atlantic Drift flow and NADW formation. Figure 2 illustrates the double feedback loop involved in the oscillation. This is indeed a complex oscillation because cyclic changes in rates of deep-water formation of two water masses occur, in which Antarctic Bottom Water production in the Southern Ocean is increased by positive feedback from the North Atlantic, and NADW production in the North Atlantic is decreased by negative feedback from the Southern Ocean. Without the negative feedback the natural tendency of the Drift salinity would be to remain as high as the Gulf Stream water and the Mediterranean outflow can make it, with a resulting large and stable rate of NADW formation. On the other hand, without NADW input to the Southern Ocean the tendency of the Antarctic Bottom Water formation is to go to and remain at a low minimum value. It is easy to see how the addition of higher or lower salinity water to the seas east of Greenland would alter the density of the surface water, and therefore could increase or decrease the NADW rate of sinking when it is cooled. In the Southern ocean, modulating Antarctic Bottom Water formation is not as simple. There is a paradox because the input of slightly warmer and more saline intermediate-level NADW to the Southern Ocean decreases the presence of sea ice and yet it increases Antarctic Bottom Water formation caused by sea ice freezing, as discussed in Sect. 4. But first, consider the various factors that enable the formation of NADW, which drives the oscillation.

3 North Atlantic deep water formation in the Greenland Sea

The surface waters of the North Atlantic have higher salinities than any other major ocean, and the North Atlantic Drift brings the saltiest of this warmer water from the Gulf Stream into the high latitudes (Fig. 3). The Drift branches into the Irminger Current and the Norwegian Current. The Spitsbergen-Atlantic Current (SAC) is then drawn northward from the Norwegian Current to replace the NADW that sinks in the seas east of Greenland. The northward flow of the SAC is geostrophically anomalous and its existence probably depends largely on its replacement of water sinking in the Greenland

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Sea, although the partial bar to flow of Norwegian Current caused by the edge of the Barents Sea shelf might contribute to the northward flow. For any variation in the rate of NADW formation, there will be corresponding variations in the SAC and the Drift. The higher sea-surface salinity east of northern Greenland enables surface water to sink to form NADW at temperatures above the freezing point when cooled in winter. The NADW that sinks in various locations east of Greenland has been followed using chlorofluorocarbon (CFC) tracers (Smethie et al., 2000). The deep water formed is not homogeneous. One deep-water component exits southward over the Iceland-Scotland sill, but the denser NADW component flows southward over the sill in the Denmark Strait between Iceland and Greenland. After much mixing a volume flow of about 10 Sv ($1\,Sv = 10^6\,m^3\,s^{-1}$) is found south of Greenland. Components of the mixed NADW enter the deep Western Boundary Current and move southward at ~3000 m-depth to where the NADW forms a slightly warmer and more saline mixed fraction of the Southern Ocean surrounding Antarctica (Weyl, 1968). The salinity of the Gulf Stream source water largely determines the Drift and Greenland Sea salinity and resulting NADW formation rate, but water from other sources can be significant. Lower-salinity polar water that mixes into the Greenland Sea from the East Greenland Current (Fig. 3) will have a negative effect on the formation rate. The saline Mediterranean outflow has a positive effect. The western Mediterranean is about 2.2 ‰ more saline than the adjacent North Atlantic and the resulting density difference drives the saline outflow at Gibraltar (Bryden and Kinder, 1991). The outflow mixes to a buoyant equilibrium and forms an initial salinity maximum around the 1500 m-depth west of Gibraltar. The maximum extends northward and rises to merge with the near-surface salinity maximum of the Drift west of the British Isles (Reid, 1979), thus contributing directly to the Norwegian Current and the salinity of the seas east of Greenland. Antarctic Bottom Water, rich in trace amounts of dissolved silica, reaches the North Atlantic and probably also mixes upward into the Drift, but its lower salinity affects the NADW formation rate negatively. Reid (1979) reported evidence for upwelling of Antarctic Bottom Water in the Drift off Scotland in the form of greater trace amounts of silica than elsewhere in the North

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Atlantic. He attributed the upwelling to a geostrophic factor, which would be consistent with the effect of higher sub surface northward velocities off Scotland (Fig. 4) as calculated from density gradients by Greatbatch and Xu (1993). However, a circulation path from the ~4000 m-depth to the shallower depths west of the British Isles has not been identified. Nevertheless, polar water outflow into the East Greenland Current and the Mediterranean outflow into the Drift can alter NADW formation, but only the Antarctic Bottom Water that reaches the high latitude North Atlantic can supply the delayed feedback that enables the ~1500 yr-oscillation of the Drift flow and the NADW formation rate.

4 Bottom water formation in the Southern Ocean

The mechanism for bottom-water formation in the Southern Ocean involves two different zones: a broad deep-water zone around the continent, and a shallow-water zone near the continental edge. The deep ocean zone has a thin stratified surface layer due to seasonal melting of sea ice and glacial ice discharged from the continent (Fig. 5). Sea ice freezes there because the stratified sea surface layer limits deep convection and enables the surface to cool to the freezing point at the beginning of the austral winter season. The prevailing westerly winds create a circumpolar surface current around the Antarctic continent, and the geostrophic effect on the flow moves surface water northward away from the coast. The resulting upwelling brings up the warmer and more saline water from intermediate depths. The temperature of this water is about 1.5 °C (Weyl, 1968). When a specific volume of sea water freezes, the rejected salt mixes and significantly increases the density of a much larger volume of water. As described by Weyl, the large volume of denser water sinks and is at first replaced by upward convection from within the stratified surface layer. As seasonal freezing progresses, denser water containing rejected salt reduces the stratification and extends convection into the deeper and warmer water, which is then brought to the surface (Fig. 5). The warmer water tends to melt the previously frozen sea ice, which limits the amount of sea ice

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present at winter's end. The limitation is probably caused by local repetitive melting and re-freezing that is driven by further surface cooling. The net amount of sea ice present at the end of winter is therefore inversely dependent on the fraction of the Southern Ocean that is composed of somewhat warmer North Atlantic water. But regardless of the composition, the large amount of low-grade heat in the deep ocean limits the deep cooling, and no Antarctic Bottom Water forms in the broad deep-ocean zone. However, Antarctic Bottom Water does form in the shallow depths of the continent's edge zone. There the entire water column can be cooled to the freezing point, and the surface water that is made slightly denser by salt rejection during freezing accumulates and flows away down the slope of the continental shelf and into the ~ 4000 m-depths of the world's deepest oceans. The replacement water is drawn from the adjacent shallow lower-salinity surface water at the freezing point (Fig. 5). Therefore annual freezing at the continental edge is not limited by vertical convection of warmer water as it is in the broad outer zone. However, paradoxically a greater amount of edge zone freezing and Antarctic Bottom Water formation occurs when there is a greater fraction of NADW intermediate level water in the broad outer zone. This would be expected because residual sea ice cover and ice shelves in the edge zone at summer's end insulate the water from subsequent winter freezing. If NADW production increases, the fraction of warmer NADW in the outer zone then becomes larger, and less winter sea ice will form there. The result will be warmer summer conditions that erode ice shelves and leave less residual sea ice in the edge zone, thus enabling more sea ice to be frozen there the following winter, and more Antarctic Bottom Water produced. The increase eventually is felt in the North Atlantic where the low-salinity Antarctic Bottom Water tends to inhibit NADW formation and reverse its increase. If there were no delay due to transport times and mixing, the slightest change in NADW production would instantly result in a limiting negative feedback and oscillation would not occur. But mixing delays do occur, and consequently oscillating accumulations of NADW in the Southern Ocean and Antarctic Bottom Water in the North Atlantic likewise occur. The delayed effects

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can be examined by casting the model in sinusoidal form using the observed ~1500 yr periodicity found in the Drift oscillation.

5 A sinusoidal model of the intrinsic deep-ocean oscillation

Although the oscillating oceanic system is complex, the phase relations between normalized elements of the model system can be easily examined in Fig. 6. The primary factor in the oscillation is the formation of NADW in the Greenland Sea. The variation of the NADW formation rate lies somewhere between zero and the maximum that would occur in the absence of the negative Antarctic Bottom Water feedback into the North Atlantic. The variation of the rate of Antarctic Bottom Water formation lies somewhere between the high rate that occurs with the maximum fraction of NADW in the Southern Ocean, and a very low minimum rate that would occur if no NADW entered the Southern Ocean and winter sea ice and ice shelves reached the maximum possible extent. There is no a priori reason to expect a precise sinusoidal form for the unperturbed oscillation, but physical systems with feedback often oscillate sinusoidally. It has been more than 6000 yr since the last significant perturbation of the oscillation by melt water, and after at least four cycles the oscillation should have settled into its unperturbed state. The sinusoidal model can be tested by anchoring the model parameters to the early medieval climatic optimum and comparing model predictions with the records of more recent times. The maximum rate of NADW formation and Drift flow is set at the medieval climatic optimum on the blue curve at AD 1000 (Fig. 6). The minimum presence of Antarctic Bottom Water in the North Atlantic that enables the NADW maximum is likewise set at AD 1000 on the black curve. The maximum rate of increase of the NADW component in the Southern Ocean is the inflection point on the red curve, and is assumed to occur at the time of maximum NADW formation under the assumption that the transport time is short relative to the time needed for mixing to make a significant change in the composition of the Southern Ocean. The maximum rate of decrease of the Antarctic winter sea ice area coincides with the maximum

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rate of increase of NADW in the Southern Ocean, with the inflection point of the falling green curve also at AD 1000. Despite short-term climate fluctuations, the underlying trend of climate change follows the sinusoidal model quite well. Consistent with the falling rate of NADW formation and decreasing Drift flow (the blue curve in Fig. 6), the first indications of cooling appeared in the higher-latitude North Atlantic two centuries after the maximum of the Drift. At about AD 1200 sea-ice began to clog the usual sailing route between Iceland and Greenland at latitude 65° N (Lamb, 1995). As the Drift flow and the NADW formation continued to decrease, cooling increased and about AD 1340 the Norse began to abandon their western colony on Greenland. Sometime soon after AD 1400 further cooling brought an end to the more southerly eastern colony also (Lamb, 1995; Seaver, 1996). That ending occurred at about half of the predicted amplitude of the change in the rate of NADW formation. The high-latitude cooling continued and, near the blue curve minimum of NADW formation about AD 1750, the most severe winters in northern North Atlantic regions occurred in the depths of the Little Ice Age. The hardships of northern Europeans were extensively documented (Lamb, 1995). Higher-altitude farms in the British Isles and Scandinavia had been abandoned and thick ice on the River Thames in London enabled winter ice carnivals. Well to the north on Iceland, the effects of cold associated with the lower half of NADW cycle lasted for almost six centuries until about AD 1850 (Lamb, 1995), a century beyond the minimum. During the minimum years, sea ice often surrounded Iceland and extended on occasion eastward to northern Scotland and beyond 0° longitude almost to Norway (Lamb, 1972; Lamb, 1995). The correlation of the model with the record is even more significant in the Antarctic region. Broecker (2000) has noted evidence from CFC-11 trace measurements indicating that: "The formation rate of ventilated deep water in the Southern Ocean is currently several times smaller than its average for the last deep ocean-mixing cycle (that is ∼ 800 yrs)." Over the last two decades the measurements indicate an average rate of Antarctic Bottom Water formation of only 4 Sv. In the model the Antarctic Bottom Water formation rate (red line in Fig. 6) is now almost at its predicted minimum. The preceding 800 yr include the model maximum, and all those red

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line values are well above present and are quite consistent with Broecker's citation. As explained in Sect. 4, the Antarctic sea ice area (green line in Fig. 6) is inversely related the Antarctic Bottom Water formation rate. In the model, the sea ice area is now approaching a maximum. Likewise in the real world, the winter sea ice attained a new historical record maximum area in 2013, as reported on the NASA web site: http://earthobservatory.nasa.gov/IOTD/view.php?id=82160. The frequent annual high values have increased over the last thirty years from about 19.0×10^6 km^2 to about 19.4×10^6 km^2, which is an increase consistent with the approaching maximum of the model. The data cannot precisely confirm the sinusoidal shape of the oscillation, but the fact that Antarctic Bottom Water formation is at a record minimum and Antarctic sea ice area is at a historical record maximum at the predicted time, a thousand years after the medieval climatic optimum, is impressive support for the sinusoidal model. The model also can provide insight to an older controversial deglaciation.

6 A failure of the oscillation: a melt water flood from Eurasia

Arkhipov et al. (1995) published a study of drainage from the massive Eurasian ice sheet around 140 000 yr BP that points to a cessation of NADW formation and the world wide loss of deep-ocean ventilation. The result of the cessation was an anomalous deglaciation during which world sea level rose to ~ 5 m above present (Johnson, 2001). The anomalous events began at the maximum of a large volume of world glacial ice, probably about 140 000 yr BP at a time of quite low world sea level. The Eurasian ice sheet then extended from Scotland to the Lena River in far eastern Siberia (Arkhipov et al., 1995). It is now possible to reconstruct the subsequent events that caused the loss of all the major thermohaline circulation in Northern and Southern oceans. At that time, glacial flow had blocked nearly all the Eurasian rivers draining into the polar ocean, and the seasonal melt water from the southern glacial front had formed a giant lake east of the Urals. The lake eventually overflowed through the Aral, the Caspian, and the Black Sea into the Mediterranean, catastrophically eroding the sediment barrier in the

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Turgai Pass north of the Aral Sea. Likewise when the flood first reached the Black Sea at its arid glacial climate sealevel well below present, it would have filled the Black Sea and catastrophically eroded away a repetitive sediment dam in the Bosporous Strait that was analogous to the present 35 m-thick sediment deposit on the bedrock of the Bosporous sill. The resulting flood into the Mediterranean would have capped it with low-density water, which continued to pour into the North Atlantic through the Gibraltar Strait. That low-salinity water diluted the Drift and stopped NADW formation. Without any NADW water entering the Southern Ocean to limit the freezing of sea ice on the deep ocean (Weyl, 1968), the thick winter sea ice area expanded northward beyond its present limit, and significant amounts of Antarctic Bottom Water no longer formed. With both Northern and Southern thermohaline circulation shut down, a predictable world wide partial deglaciation began and the world's deep oceans stagnated. In the Antarctic area, the circumpolar storm systems followed the jet stream that was located over the sea-ice/ocean zone of strong thermal gradient. The storms therefore would have traveled on paths much more distant from the continent, and precipitation on the Antarctic continent was greatly reduced. A net annual loss of the continental ice then occurred because the ice streams continued to carry ice from the continent into the sea at about the former rate. In the North Atlantic the lack of NADW formation would have greatly reduced the Drift flow and allowed the oceanic polar front to extend well to the south, probably to the Gulf Stream and the latitude of northern Spain. The strong temperature gradient across the polar front at about latitude 40° N would then have caused a zonal jet stream pattern that pulled the storm tracks away from much of the ice sheet area in northeastern Canada. Lack of precipitation and cloudless summer skies would therefore have caused the ice sheets in the Greenland and Laurentide areas to diminish, and their melt water contributed to the capping of the northern North Atlantic. On the east side of the North Atlantic the eastward zonal atmospheric flow at the latitude of Spain would have limited winter precipitation on Eurasian ice sheets. In summer the temperature gradient and jet stream associated with the cold ocean and adjacent warmer land of southwestern Europe would have directed a flow of warmer

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dry air northeastward over the ice sheets. This kept melt water draining through the Black Sea and Mediterranean until the southern front of the ice sheet retreated across the divide into the Baltic area. The melt water discharge through the Mediterranean Sea then stopped. The melt water cap disappeared, and it is easy to see how the intrinsic oscillation would have soon been re-established. If the melt water cap on the Greenland Sea were removed within a few decades, for example, a high rate of NADW formation would have begun. The NADW fraction in the Southern Ocean would have rapidly increased, thus diminishing the extensive Antarctic winter sea ice and increasing the Antarctic Bottom Water formation from its initial near-zero rate. The subsequent buildup of Antarctic Bottom Water in the North Atlantic would then have reduced the NADW formation rate and completed a first half-cycle of the oscillation. After probably only a few centuries of peak sea level, rapid ice sheet growth resumed on all the partly deglaciated ice sheets. Sea level quickly fell to another low point (Esat et al., 1999) before the deglaciation began that rapidly raised the world sea surface to the high last interglacial sea level, again about 5 m above present. The earlier anomalous high sea level about 136 000 yr BP has encountered much skepticism because it occurred during a minimum of Northern summer solar insolation. It therefore violates the widely accepted Milankovitch hypothesis that predicts large ice volumes at times of low insolation. Also, the marine oxygen isotope proxy for glacial ice volume, upon which the Milankovitch hypothesis is based, shows little indication of a massive deglacial melt water event. Consequently the significance of the melt water flood into the Mediterranean and the long-standing observations of the anomalous high seastand on Barbados (Johnson, 2001) and New Guinea (Chappell, 1974) have been largely ignored. There are, however, reasons for the failure of the ice-volume proxy as derived from various deep-sea sediment cores at that time. The resolution on a thousand year time scale in most deep-sea cores is poor because the deposition rates are low and some sediment mixing occurs. Therefore a narrow anomalous melt water spike in the oxygen isotope ratios would tend to be flattened. The benthic foraminferal species that live on the bottom sediments in a nearly constant temperature environment are the preferred

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species for the ice volume proxy measurement. But during the stagnant interval they would have been largely isolated from the melt water inputs, and so retained most of the full glacial isotope ratio value. In the case of the planktonic species living at the sea surface much of the true glacial-interglacial isotope ratio signal in the sediments is attributed to a climate temperature increase, an increase which did not occur because the anomalous glaciations of Northern and Antarctic ice sheets were not completed and most of the world climates would have remained cold. Consequently the visible change in isotope ratio values for most planktonic species was relatively small and hardly visible after the sediment mixing occurred and flattened the spike. Therefore a large glacial ice volume and low sea level were incorrectly inferred. But the wave-cut notch that formed during that brief time when world sea level was at a maximum above present is clearly visible at a few favorable locations on uplifted Barbados (Johnson, 2001), including the edge of the football pitch on the campus of the University of the West Indies. That brief high sea-stand is dated to about 136 000 yr BP when all uplift factors are taken into account. It is therefore a much more accurate proxy for ice volume than the deep-sea oxygen isotope ratios at that time. The melt water flood through the Mediterranean was an unknown and unexpected event before the Arkhipov et al. (1995) study. The Mediterranean outflow might be the source of another quite different unexpected climatic event in the near future. This possibility is suggested by historical events of almost a thousand years ago.

7 Implications of the historical record: open water off northern Greenland

The latest oscillation maximum in the Drift occurred around AD 1000, and historical events suggest that a warmer climate than today prevailed off the Greenland coasts (Lamb, 1995). In addition to the Norse colonies in southern Greenland, Norse activity also occurred to the north beyond latitude 79° N in the Kane Basin within the Nares Strait off northwestern Greenland (Schledermann, 2000). Norse items found there on Skraeling Island included a carpenter's plane, a piece of chain-mail, and woven cloth

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that was carbon 14 dated to AD 1190 ± 60. Of even more significance, two Norse landmark cairns were found on Washington Irving Island, 40 miles farther north in the Basin. A unique map from a Church archive strengthens the support for medieval Norse activity in the high arctic. This map was drawn, or redrawn, by a Jesuit in AD 1599, and it depicts Greenland as an island with a realistic outline, together with the Vinland coast of northeastern Canada (Ingstad, 1969). Other maps drawn by explorers of post Columbus time show Greenland connected to the continent because they were unable to sail beyond the perennial sea ice enclosing the northern coasts. Therefore the Jesuit map was apparently drawn using information from a map made at an earlier and warmer time. The Jesuit's source was likely a map by Bishop Erik Gnupsson who is known to have visited Greenland and Vinland in AD 1117 and 1118 (Skelton et al., 1965), probably on a merchant ship. The Norse names on the map, "ioten heim", for Ellesmere Island, "Narre Oe" for the ice-free Svalbard archipeligo, and the depiction of Greenland as a realistic island can be taken as evidence that after his Vinland visit Bishop Gnupsson sailed onward around northern Greenland in waters warmer than in the Jesuit's time. His voyage would have been possible only if the thick perennial sea ice, which today covers the sea along the northern coast of Greenland, had been absent in AD 1118. The present branches of the North Atlantic Drift do not warm the sea north of Greenland. However about the year AD 1100 near the maximum of the ∼ 1500 yr-cycle, stronger NADW formation probably extended the SAC flow significantly into the polar ocean. Apparently that extension blocked the polar ocean outflow into the East Greenland Current and enabled some warmer saline Atlantic water to enter the westward flow along the northern coast of Greenland, thus removing the perennial sea ice along the northern coast. This probably began as an abrupt event because the blockage of low-salinity polar water flow into the East Greenland Current would have provided positive feedback favoring a rapid increase in Greenland Sea salinity, the rate of NADW formation, and a stronger SAC flow. However, any Atlantic water entering Baffin Bay through the Nares Strait was then insufficient to destroy the stratification there, in contrast to

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the stronger inflow inferred from the ice-free Baffin Bay on the threshold of the last ice age.

8 Initiation of the last ice age: the ~500 yr threshold interval

The first Canadian glaciation of the last ice age began with extremely heavy precipitation and a world sea level fall beginning about 120 000 yr BP, the radiogenic age of youngest corals on a reef now slightly above sea level in western Australia (Stirling et al., 1995). The evidence suggesting heavy precipitation in the Baffin Island region, precisely at the time new glaciation began, comes from Devon Island at the north end of Baffin Bay (Fig. 3). Devon Island became free of glacial ice during the last interglacial, 126 000 to 120 000 yr BP, but the icecap that formed subsequently during the last ice age has not melted away. An ice core extracted from this icecap extended down to bedrock (Koerner et al., 1988). When glaciation began, the oxygen isotope ratios of the lowest layers in the core showed that the ice was composed of snow that had precipitated under warmer and more humid conditions than snow in layers above. The lowest layers also received wind- blown sediment and grains of willow pollen. In today's interglacial no willows grow closer than the distant Chantrey Inlet, about 600 miles southwest of Devon Island (Short et al., 1985). The oxygen isotope ratios and willow pollen in ice at the base of the core therefore show that the normally dry and severe winter climate of Devon Island had been replaced by wetter winters that are consistent with a warmer regional climate and the absence of winter sea ice cover on Baffin Bay. Evidence for even greater sea surface warmth is found in the Labrador Sea 200 km east of southern Baffin Island (Fig. 3) at the site of core HU75-58 (Fillon, 1985) where winter sea ice prevails today. Near the threshold of the last ice age, indicated by an abrupt shift toward positive oxygen isotope ratios in foraminifera, a high 60 % abundance of skeletons of warm-water sub polar species of foraminifera occurred in the core sediments (Fig. 7). Although the ice-free interval at the north end of Baffin Bay and the more extreme warmth of the Labrador Sea south of Cape Dyer are not precisely

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dated, it is most likely that they were concurrent, and were caused by the same regional change in oceanic and atmospheric circulation. With open sea conditions as far north as Devon Island, the warmer water at the HU75-58 site can be attributed to a stronger Irminger Current and the absence of sea ice that today is frozen in Baffin Bay and is carried southward by the Canadian Current as far as Newfoundland. The increased warmth of the Labrador Sea, largely surrounded by cold land, would then have enabled a strong cyclonic circulation west of Greenland with wind stresses that strengthened the West Greenland Current, thus further increasing Labrador Sea temperatures. This persistent cyclonic flow brought heavy precipitation to widespread land areas west of Greenland. The nearly continual cloud cover would have protected the heavy snows from solar radiation and thus would have favored rapid glacial ice sheet growth on Baffin Island, western Greenland, northern Quebec, and Labrador, causing equally rapid world sea level fall. The widespread precipitation and erosion explains the sharp ∼ 500 year pulse of clay and red hematite-stained sand grains in Fig. 7 (Adkins et al., 1997) that is found in the higher resolution record of core MD96-2036 from the Bermuda Rise, in which data points are separated by about 300 yr. Deep currents carried these sediments from areas bordering the Labrador Sea and Baffin Bay. The persistent cyclonic circulation over the warm Labrador Sea apparently prevented the usual development of low-pressure circulation systems over nearby Iceland, which today are important for transporting warmer air into northern Europe. Therefore northern Europe had an interval of severe cold that caused a loss of temperate climate trees in Germany (Field et al., 1994), a loss indicated by absence or near disappearance of their pollen in lake sediments (Fig. 8). The length of this ice-age threshold interval is roughly 500 yr, as defined by the duration of the hematite-stained sediment pulse in Fig. 7. In the absence of the frequent cyclonic circulation centered near Iceland, strong westerly wind stresses on the sea surface would no longer have inhibited the westward flow of the Irminger Current (Fig. 3), and wind stresses favoring the Norwegian Current would have been diminished. The Irminger Current would therefore have been enhanced at the expense of the Norwegian Current. The weak Norwegian Current would

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have strengthened the colder temperatures in Northern Europe and would quite likely also have allowed the growth of a potentially unstable glacial ice dome, grounded in the shallow and much colder Barents Sea in the path of traveling storm systems north of Norway. The weaker Norwegian Current suggests that less salt entered the seas east of Greenland, and that Atlantic water no longer entered the sea north of Greenland. Yet the seas west of Greenland remained ice-free under the strong cyclonic circulation for ~ 500 yr, probably because of higher sea level in Baffin Bay. The cyclonic circulation enhanced the flow of the West Greenland Current carrying saline Atlantic water into Baffin Bay, where NADW would have formed by winter cooling. The northward replacement flow would have brought additional warmth to the Labrador Sea, and so enhanced the persistent cyclonic circulation, thus forcing even more water northward. The higher sea level there could then have prevented the southward flow through the Nares Strait and the minor inflow through Lancaster Sound, flows that are usually driven by higher polar atmospheric pressures. I have observed the dominant southward flow through the Nares Strait, and also the effect of just such a temporary higher sea level in Baffin Bay. Observations of movements of large clumps of ice floes during 2011, made using the European Space Agency's ENVISAT images posted twice daily, showed that on 94 % of the days when flow was observed, the north or south flow direction through the Nares Strait correlated with the respective atmospheric pressure differences between the polar ocean and Baffin Bay. In one exceptional case, around 16 March 2012 and shortly before the failure of the high resolution ENVISAT system, a cyclonic low-pressure center passed over southern Baffin Island (Fig. 9). Wind stresses moving water northward apparently caused a higher sea level in Baffin Bay than over the polar ocean, because northward movement of clumps of ice floes on the polynya in the south end of Nares Strait was observed the next day despite a higher polar atmospheric pressure. The ongoing persistence of cyclonic circulation causing an elevated sea level in Baffin Bay is the likely explanation for the lack of significant polar water flowing southward through the Nares Strait during the ~ 500 yr-interval of ice-age threshold climate.

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9 Ending the threshold climate interval

The threshold climate in Europe probably ceased when the cyclically increasing input of Antarctic Bottom Water to the North Atlantic reduced the salinity of the North Atlantic Drift. The resulting decrease of NADW formation in Baffin Bay would have weakened the West Greenland Current, and negative feedback would soon have ended deep-water formation there. This allowed the sea surface stratification and winter sea ice conditions to return, destroying the cyclonic circulation and ending the ~500 yr ice-age threshold climate interval in Europe. A restored warm Norwegian Current would have rapidly destabilized and melted the marine-based Barents Sea ice dome, and the pollen of temperate climate trees returned to the record in northern Germany (Fig. 8). A slightly cooler interglacial climate then prevailed in Europe for ~4000 yr until a great Hudson Bay jokulhlaup occurred (Johnson and Lauritzen, 1995). Although European interglacial warmth prevailed during this interval, ice sheet growth continued in north-eastern Canada and world sea level continued to fall, but more slowly. The rapid loss of a Barents ice-dome probably caused a brief sea level rise ~500 yr after sea level fall began. This could explain the minor wave-cut notch or step observed on tectonically uplifted Barbados at several locations at the top of the First High Cliff, the large coral reef deposited during the last interglacial (Johnson, 2001). After a small uplift correction at the Cane Vale B site, the surveyed elevation difference was 2.5 m between the flat of the notch and the higher constant interglacial sea level at the surface of the nearby mature interglacial barrier reef that was abandoned when the rapid sea level fall began (Johnson, 2001, Fig. 2). This stratigraphic difference indicates an average rate of sea level fall of ~5 mm yr^{-1} during the ~500 yr threshold climate interval. There is no reason to expect a large increase in ice volume on Antarctica at this time. But the ice core and deep-sea sediment records imply meteorological conditions in the lands west of Greenland and in the Barents Sea area that would be consistent with high rates of accumulation and the estimated rate of sea level fall. The possibility of a modern climate switch to these threshold meteorological conditions is not negligible.

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10 A modern threat

The next expected Drift oscillation maximum that could threaten a new ice age would occur about AD 2500 (Fig. 6), but strong warming due to rising CO_2 concentration in the atmosphere might then make the initiation of ice sheet growth impossible. However, two other factors attributable to mankind's activities might make the ice-age threat a reality much sooner before CO_2 warming becomes prohibitive. They are: the loss of polar ocean perennial sea ice due to CO_2 warming, and an increasing saline outflow from the Mediterranean due to the damming of inflowing rivers for irrigation. The effect of increasing Mediterranean outflow is suggested by the strong SAC flow that now maintains ice-free water in winter north of Spitsbergen. The flow appears to be almost as strong as when penetration occurred north of Greenland during the latest Drift maximum about 1000 yr ago, and the increase seems to be of modern origin. During the latest minimum of the NADW formation rate and the Drift flow about the year 1750 (Fig. 6), the SAC flow was quite weak. The northern limit of ice-free open water in the Greenland Sea maintained by the SAC in winter would have remained well to the south, consistent with the winter sea ice that sometimes completely surrounded Iceland, as it did in AD 1695 (Lamb, 1972, Fig. 8.12) and extended eastward to the 0° meridian. But in the first part of the 20th century open water due to SAC flow extended farther north to almost 77° N latitude, rarely reaching 80° N. In recent years the usual winter flow has even reached beyond the Fram Strait, maintaining open water as far as latitude 83° N north of Spitsbergen as in 2013 and 2014 (Figs. 10 and 11). This increasing strength of the SAC flow implies a matching rise in the Greenland Sea salinity. Some of the increase in the Greenland Sea salinity since the Little Ice Age is probably due to the expected cyclically-diminishing amount of Antarctic Bottom Water in the North Atlantic, as shown by the falling black curve in Fig. 6. A slow increase in Mediterranean salinity and outflow rate through the Holocene has also occurred because of an orbital effect. African monsoons, influenced by decreasing Northern Hemisphere orbital summer insolation at the northern African latitude of 30° N, have weakened since the

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Mediterranean and North African pluvial period early in the Holocene (Rossignol-Strick, 1983) near the summer insolation maximum. A similar trend of orbital change and weakening insolation is also found after the early pluvial interval of the last interglacial (Rossignol-Strick et al., 1998) with a similar decreasing insolation (Fig. 8). This may have been a factor in the termination of many other Pleistocene interglacials during the last million years. However, the modern increase in SAC flow and the related increase in the Greenland Sea salinity over the last 50 yr cannot be attributed to an orbital effect because insolation at 30° N has now passed a minimum and is slowly increasing (tabulated data, Berger, 1978). However, the recent increase in salinity of the Greenland Sea inferred from the SAC flow has probably been caused by an artificial increase in the Mediterranean outflow. I estimate that Mediterranean river inflows compensated for almost 30% of its net evaporation losses of about 35 000 $m^3 s^{-1}$ prior to the 20th century. But since AD 1950 most of the flows of major Mediterranean rivers have been diverted for irrigation. Consequently the Mediterranean salinity has begun a more rapid rise, a rise that will continue for at least another century, as suggested by the Mediterranean e-fold mixing time of about 120 yr based on the exchange current rates at Gibraltar. In the last 60 yr the measured salinity of the deep western Mediterranean has increased by about 0.05 ‰ (news item, Science, 1998, v. 279, p. 483). The 0.05 ‰ is equivalent to a ~ 2.3 % increase in the density difference between Atlantic and Mediterranean water that drives the outflow at the Gibraltar sill. Consequently, the outflow rate is likewise increasing and is adding salt to the Drift and the Greenland Sea. The more rapid outflow will have greater turbulent mixing and will therefore equilibrate at a shallower depth and mix more efficiently into the Drift. The modern northward subsurface flow rates at latitude 54.5° N (Fig. 4) as calculated by Greatbatch and Xu (1993), together with the transect of Reid (1979) suggest that the influence of the outflow may be confined to the Norwegian Current and may not extend westward to the Irminger Current in modern times. Thus a density difference increase of at least ~ 2.3 % has probably caused a significant salinity increase in the seas east of Greenland. It has apparently brought NADW formation and the SAC flow close to the triggering point for the ice age

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threshold climate. In the coming hundred years, if world wide CO_2 warming increases its net evaporation losses, the continuing increase of Mediterranean salinity would be even larger, and might bring the SAC flow to the triggering point. However, that point might be reached much sooner. The net melting of perennial polar sea ice will cease when all the perennial sea ice is gone in the near future, as suggested by the trend in Fig. 12. This suggests a possible climate-changing increase in the salinity of the polar ocean and the Greenland Sea. The large average decrease in the area and thickness of perennial polar sea ice over the last two decades implies net annual melt water additions that lower the polar water salinity. This lower-salinity water mixes into the sea east of Greenland from the East Greenland Current and tends to reduce NADW formation. The net melt water addition will no longer occur after the perennial ice is gone. The resulting salinity increase of the polar ocean cannot be accurately estimated, but it is likely to be significant. Assuming a final perennial sea-ice melting rate as approximated using Fig. 12, I estimate that the cessation of net melting would enable an increase in polar water salinity equivalent to a 10–15 % reduction of the river discharges into the polar ocean. In only a few years, the rise in the salinity of the polar water entering the East Greenland Current and the absence of perennial sea ice melting there will then allow an increase in the salinity of the Greenland Sea and the NADW formation rate. The increased SAC flow might then completely block the southward flow of polar water into the East Greenland Current. The resulting further abrupt increase in Greenland Sea salinity and SAC flow could then send Atlantic water into the sea north of Greenland, possibly within less than two decades from 2013. If significant penetration of Atlantic water into the northern coastal sea off Greenland then occurs, it would, at the least, maintain a mild regional climate like the climatic optimum in the higher North Atlantic latitudes a thousand years ago. At worst, it would eliminate stratification in Baffin Bay and switch on the ice-age threshold climate. Beyond the threshold, a glacial climate in Canada might not continue indefinitely in the face of strong CO_2 climate warming. However, if the switch occurs, the ice-age threshold climate would prevail at the least for many decades, and would have a disruptive effect on higher latitude societies.

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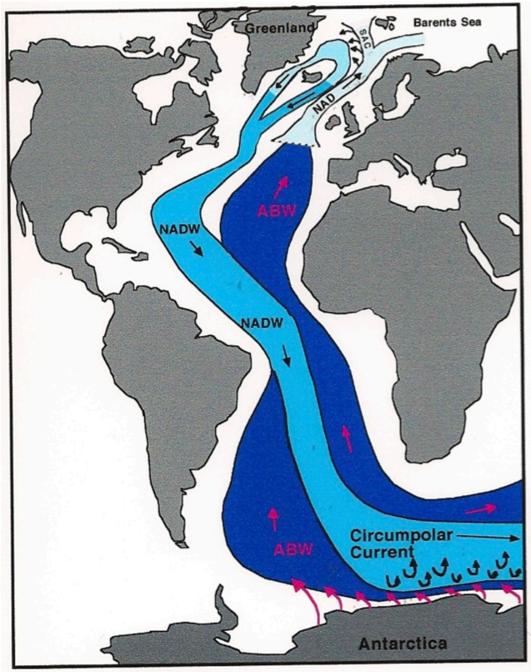

Figure 1. Schematic exchange of water masses between northern and southern high latitudes. ABW: Antarctic Bottom Water. NADW: North Atlantic Deep Water. NAD: North Atlantic Drift. SAC: Spitsbergen-Atlantic Current Surface water in the seas east of Greenland sinks to intermediate depths and moves southward to the Southern Ocean. There it upwells in a broad zone around Antarctica. In the shallowest depths at the edge of the continent, water that is made slightly denser by salt rejected from sea ice during freezing flows down over the continental shelf to the bottom of the deepest world oceans.

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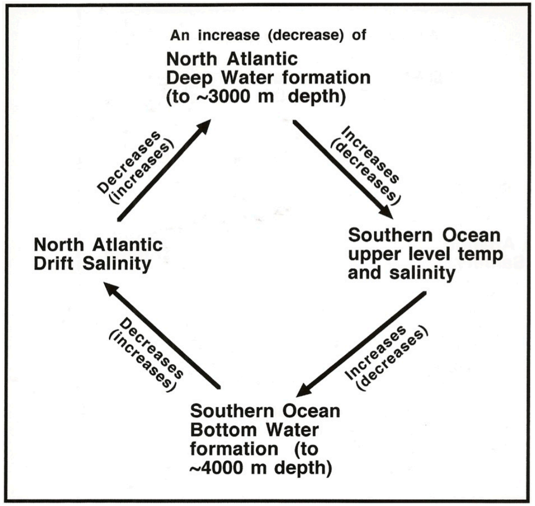

Figure 2. The double feedback loop that drives the deep ocean oscillation with an approximate periodicity of 1500 yr. This diagram helps to visualize the linkages and feedback that cause the oscillation. However, the sinusoidal model depicted in Fig. 6 is needed to show the phase relations between the various factors of the oscillating system.

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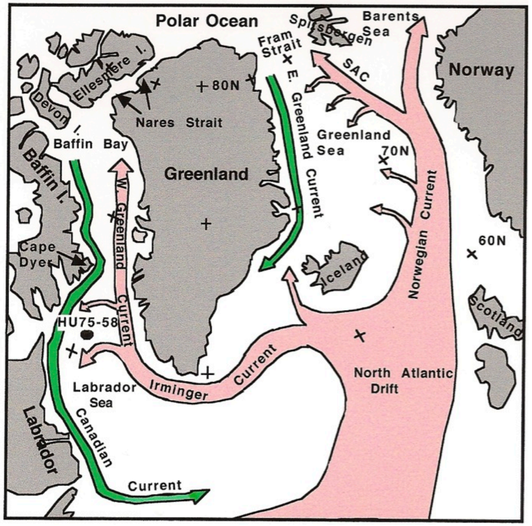

Figure 3. Major transport paths for upper level water in the high-latitude North Atlantic. Although customarily labeled as currents, drifter instruments show much erratic motion. The dominant southward flow through the Nares Strait is not shown.

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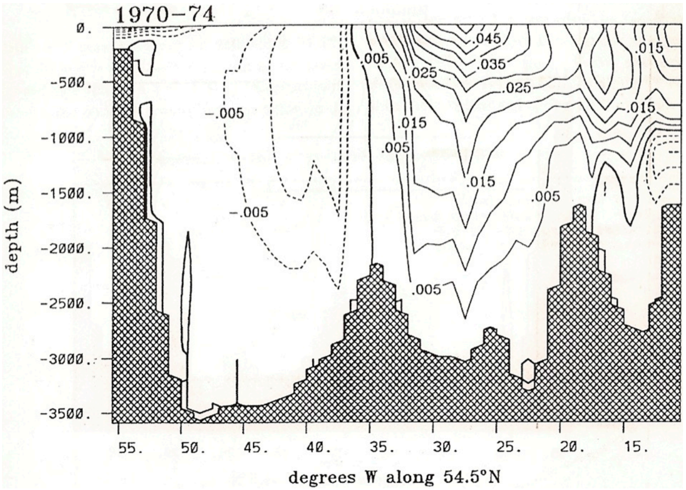

Figure 4. Average northward oceanic flow velocities at 54.5° N in a vertical cross section west of Ireland during the 1970–1974 pentad as calculated by Greatbatch and Xu (1993) from density data. Velocities are in $m\,s^{-1}$. The distinct pattern of stronger flow between 14 and 19° W suggests a higher salinity due to the presence of Mediterranean outflow water, which supports the importance of the outflow contribution to North Atlantic Deep Water formation. These velocities would not include components due to wind stresses or the northward movement needed to replace sinking deep-water. Used with permission of the American Geophysical Union.

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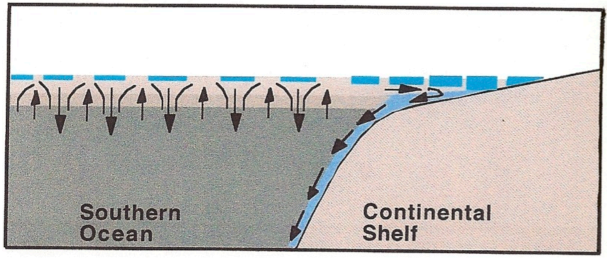

Figure 5. Antarctic Bottom Water (ABW) formation. This water mass is formed by sinking in the shallow water at the edge of the continent where salt rejected by freezing makes the water more dense, and replacement water can come only from adjacent cold surface water. Over deep areas more distant from the coast, the replacement for the down-fingering saltier water formed during freezing eventually comes up from somewhat warmer water below. The heat brought up limits the amount of sea ice present at the end of each winter.

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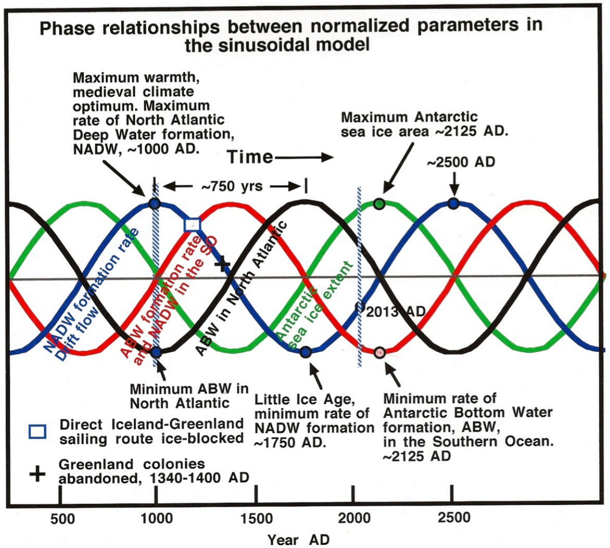

Figure 6. Phase relationships for normalized variables in a sinusoidal model of the intrinsic deep-ocean oscillation. NADW: North Atlantic Deep Water. ABW: Antarctic Bottom Water. NAD: North Atlantic Drift. SO: Southern Ocean. External factors such as melt water and the presently increasing Mediterranean outflow are ignored. Each normalized parameter oscillates around its positive average value with a 1500 yr period. Note that in year 2013 the model correctly predicts a sea-ice area maximum in Antarctic winter, and a minimum in Antarctic Bottom Water formation. See text.

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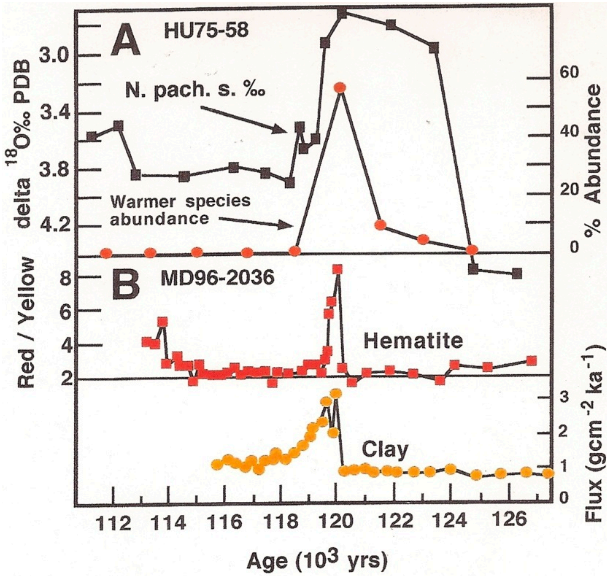

Figure 7. Regional climate switch indicators as the last ice age began. **(A)** Oxygen isotope ratios of a cold-water species of planktonic foraminifera and the abundance pulse of warmer water species in core HU75-58 east of southern Baffin Island (Fillon, 1985). **(B)** Pulses of hematite and clay in the high- resolution record of core MD96-2036 from the Bermuda rise. The width of the hematite pulse suggests a duration of ~500 yr for the threshold climate interval. These pulses resulted from large amounts of precipitation and erosion in areas bordering the Labrador Sea and Baffin Bay (Adkins et al., 1997). Measured ages were not precise. Therefore the leading edges of all pulses are set a few hundred years before the U-series age of the youngest corals that had grown on a slightly elevated reef in Australia (Stirling et al., 1995).

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Interactive Discussion

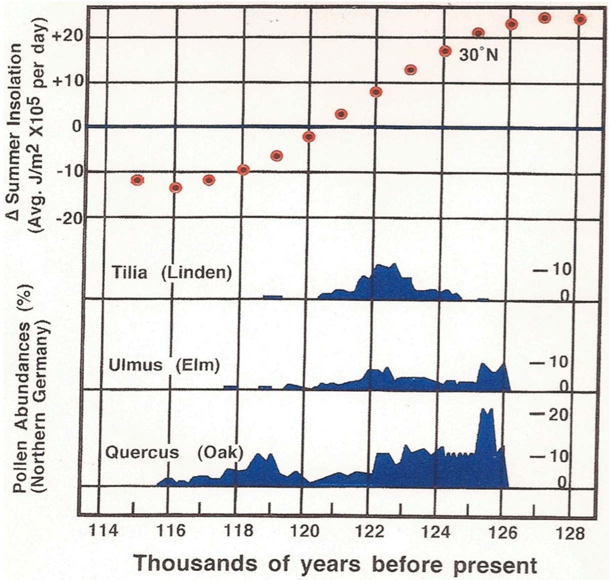

Figure 8. Temperate climate tree-pollen records from a lake in northern Germany as caloric summer insolation fell at the beginning of the last ice age. Pollen abundances from Field et al. (1994). Tabulated values of caloric summer insolation were supplied by Berger (1978). These precise insolation values are differences relative to the value for the year 1950. The time scale is set with the near-disappearance of pollen a few hundred years before 120 000 yr BP, consistent with evidence for the climate switch in the Labrador Sea region, the resulting cooling in Europe, and the dated corals exposed by falling sea level (Stirling et al., 1995). Note that the insolation value at the dated coral age is little different from today, implying that modern conditions may be close to the point of triggering the threshold climate.

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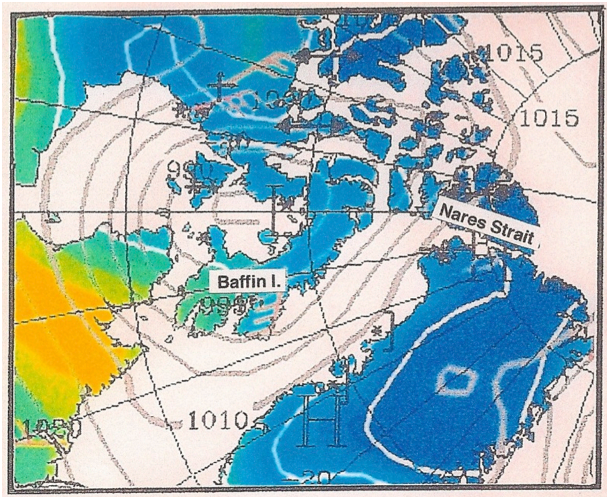

Figure 9. Cyclonic circulation over Baffin Island on 16 March 2012, at 06:00 GMT. Wind stresses elevated the sea surface at the northern end of Baffin Bay. On 17 March, northward flow in the Nares strait was observed despite a higher pressure over the polar ocean at the north end of the Strait. Polar weather map posted daily by the University of Cologne.

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Past and future ice age initiation

R. G. Johnson

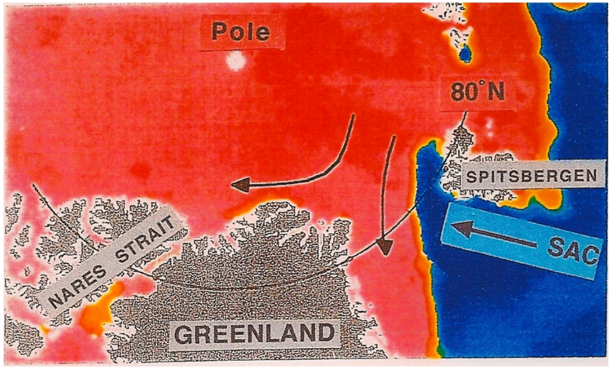

Figure 10. False color SSMIS image (red, yellow) of high-latitude sea ice in the vicinity of Spitsbergen and northern Greenland on 20 March 2013. From: www.seaice.dk/iomasa/amsr/thin/today/. The Spitsbergen-Atlantic Current (SAC) maintained open water into the Fram Strait and north of 80° N beyond Spitsbergen throughout the winter. Arrows show polar ice flow into the East Greenland Current and into the area north of Greenland, as observed with ENVISAT images.

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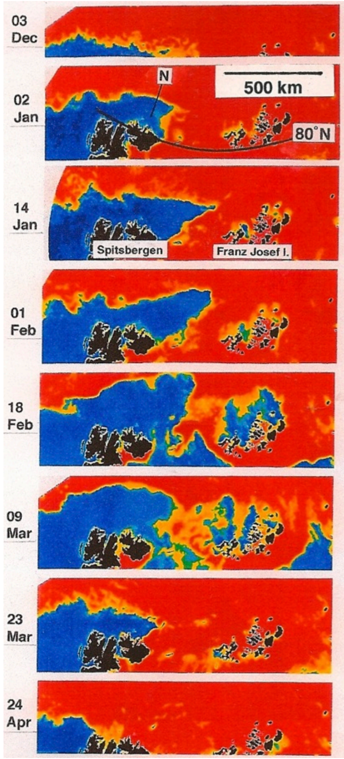

Figure 11. False color images of sea ice (red, yellow) showing penetration of the Spitsbergen-Atlantic Current into the polar ocean north and east of Spitsbergen from 3 December 2013 to 24 April 2014. The increase and decrease in penetration would reflect the flow to replace the North Atlantic Deep Water formed by sinking of saline surface water as the surface cools and then warms through the coldest part of the winter. The flow tends to be diverted northeastward because of a geostrophic effect and the opposing southward flow of the polar current (data source: http://www.seaice.dk/iomasa/amsr/thin/today/).

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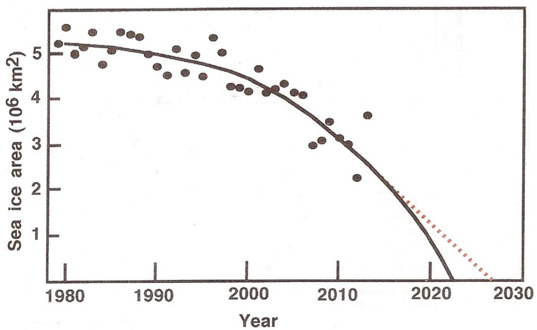

Figure 12. Annual minimum of perennial polar sea ice area since 1979. From: the Cryosphere Today: http://arctic.atmos.uiuc.edu/cryosphere/. The seasonal minimum is usually reached about 10 September. The curve is fitted by eye.

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