MILLENIAL SCALE CLIMATE VARIABILITY

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Introduction

Analysis of Quaternary marine sediment cores has changed in emphasis several times over the last four decades. In particular, this has involved a change in focus from variations in proxy records on orbital or Milankovitch timescales (with recurring periodicities of *c.* 20 000, 40 000 and 100 000 years), to an interest in the sub-Milankovitch variability (**Figure 1**). In turn that has frequently meant a change in the length of the record from several million years, to several tens of thousands of years (often the last glacial/deglacial cycle which extended from 120 000 years ago to the present). It has also meant an increased interest in sites with high rates of sediment accumulation ($\gg 10\,\mathrm{cm\,ky^{-1}}$).

Although not precisely defined, the term 'millennial scale climate variability' is usually considered to cover events with periods of between 1000 and 10 000 years. Evidence for abrupt, millennial scale changes in ocean sediments (**Figure 1A** and **B**) has resulted in a paradigm shift. The role of the oceans in abrupt climate forcing is now considered to be paramount, whereas under the Milankovitch scenario, the role of the oceans was frequently considered subordinate to changes on land associated with the growth and decay of the large Quaternary ice sheets (**Figure 2**) which were principally driven by changes in high-latitude, Northern Hemisphere insolation (e.g. **Figure 1D**).

History

The ability to undertake millennial scale climate reconstructions from marine sediments was conditioned by several requirements which could not be met until the 1980s and early 1990s. An underlying rationale for this interest were the results from the

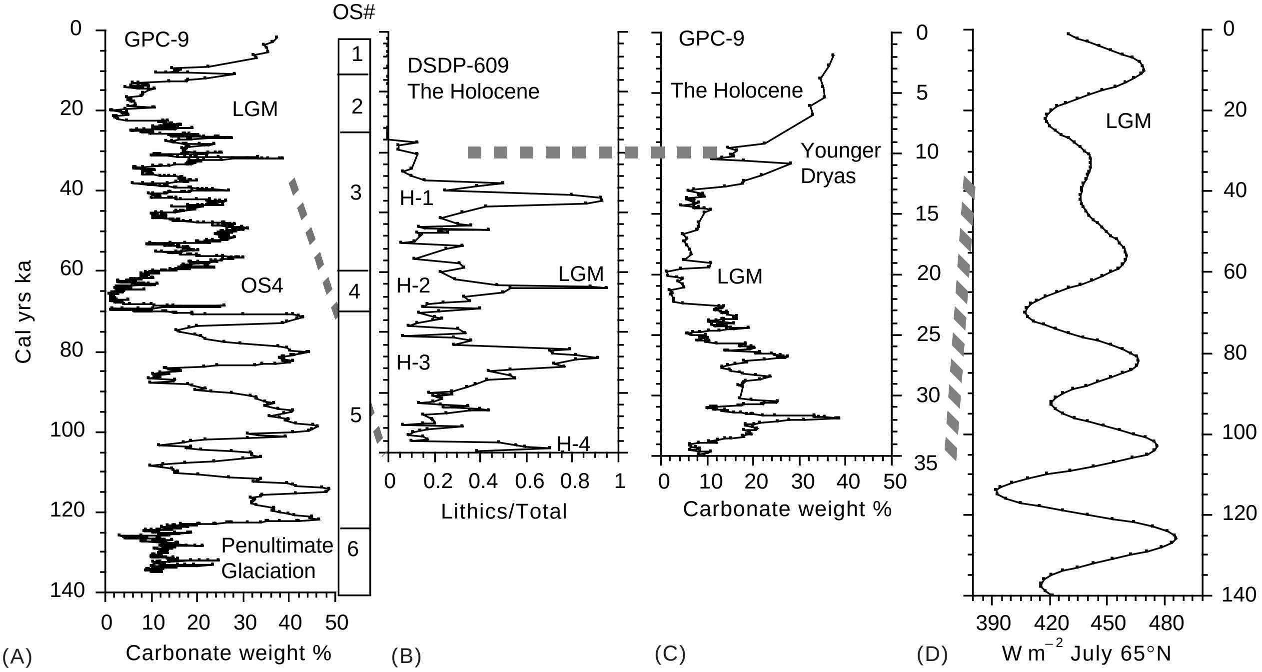

Figure 1 Examples of millennial-scale oscillations in marine records (see **Figure 2** for core locations). Data were taken from the National Oceanographic and Atmospheric Administration Paleoclimate Database (www.ngdc.noaa.gov/paleo/). Age is given in thousands of years ago (ka) and the marine oxygen isotope stages (OS) are shown. The temporal location of Heinrich events (H-1–H-3), the last glacial maximum (LGM), and the dramatic Younger Dryas cold event are shown. On the right-hand side is the summer insolation at 65°N for July. Notice the absence of millennial-scale variability in the Milankovitch forcing of global climate although the main peaks and troughs are picked out in the carbonate record (left-hand column).

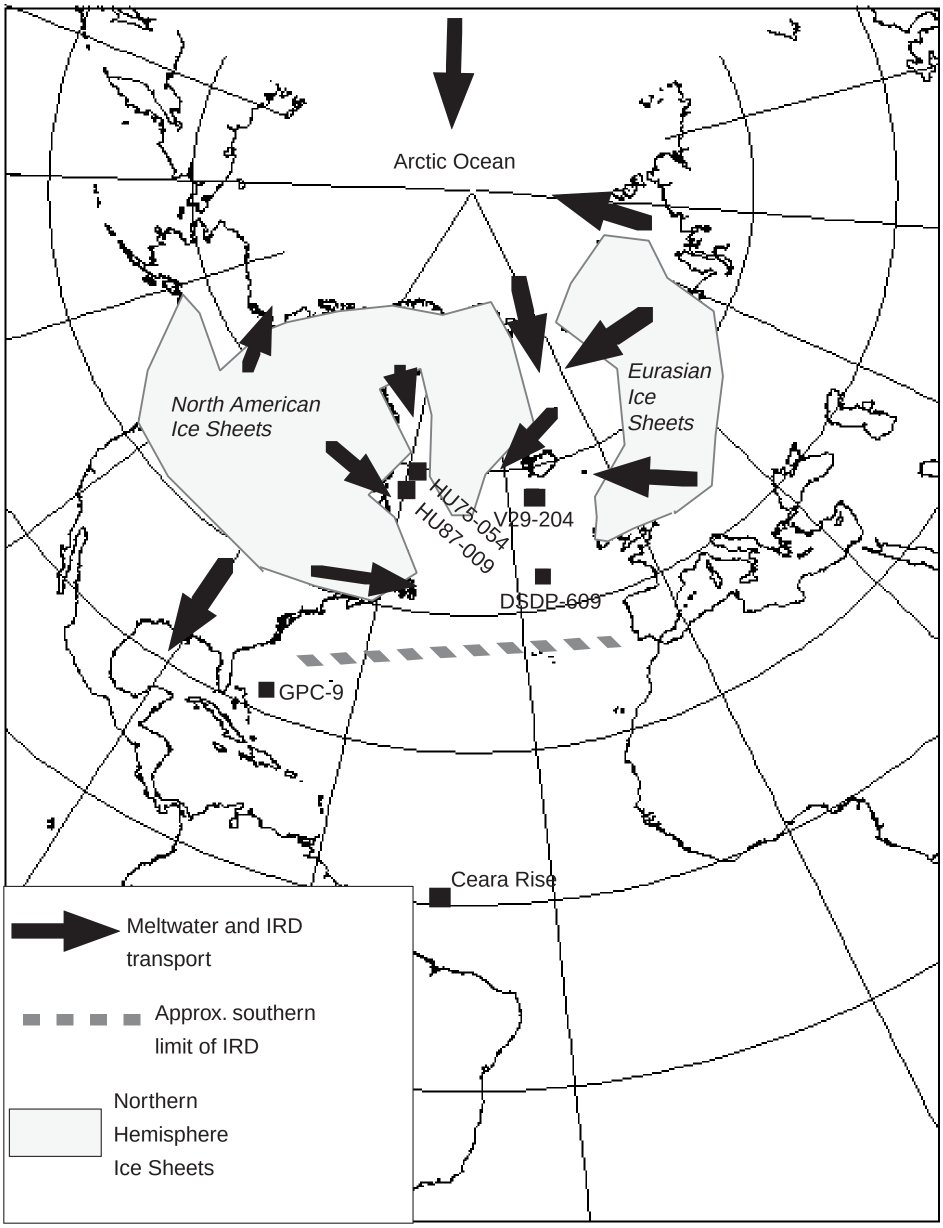

Figure 2 The glacial world of the last glacial maximum (LGM) showing routes for the export of fresh water (from meltwater, e.g., Gulf of Mexico), and the major iceberg rafted detrital (IRD) sources for deposition in North Atlantic Basins. The location of several cores mentioned in the article are shown.

Greenland and Antarctic ice core records which showed remarkably rapid oscillations in a variety of proxies for the last 40 000–80 000 years. The advent of accelerator mass spectrometry (AMS) ^{14}C dating of small (2–10 mg) samples of foraminifera allowed many of the world's deep-sea and shelf sediments to be directly dated up to a limit of between 30 000 and 40 000 years ago. Because of the small sample size required and the relatively fast turn around, it became possible to obtain many dates on a core, and in some cases the density approached one date per thousand years. This technology also meant that sediment cores from environments with high rates of sediment accumulation could now be successfully dated, thus a variety of sediment environments from the 'drifts' around the North Atlantic, to glaciated shelves and fiords, could now be studied. In these environments, sediment accumulation rates were often greater than 20 cm ky^{-1} and could reach rates as high as 2 m ky^{-1}. In areas with these very high rates of sediment accumulation there was a clear need for improved coring technology such that cores of tens of meters in length could be obtained. Giant piston cores were thus developed with recoveries in the range of 20–60 m. An example is the Calypso system deployed from the French research vessel *Marion Dufresne* and employed as part of the IMAGES (International Marine Past Global Change) program. This allowed for very high resolution studies (sediment accumulation rate (SAR) of $\geq 1\,\mathrm{m\,ky^{-1}}$, decadal resolution) if the cores recovered sediments with basal dates of 10 000 BP. If the cores were extracted from areas with more modest rates of sediment accumulation (>10 and $<100\,\mathrm{cm\,ky^{-1}}$), then millennial-scale studies were possible. However, one problem with longer temporal records was that they recovered sediments with ages greater than the radiocarbon limit of *c.* 45 ka. Records that extended back into marine or oxygen isotope stages 4 and 5 (**Figure 1**, OS column) could not be numerically dated *per se*, but their chronology had to be derived by correlation with other records. In some important but rare cases, the marine sediment is annually laminated and a chronology can be developed by counting the varves, analagous to counting ice thickness in an ice core.

The rationale for conducting high-resolution, millennial-scale studies of marine sediments has been largely driven by the need to ascertain if the abrupt climate changes recorded in the polar ice sheet records, particularly the millennial-scale Dansgaard–Oeschger events, were evident in the ocean system (**Figure 1B** and **C**).

Examples of Millennial Scale Oceanographic Proxy Records

In the last decade the number of papers on millennial-scale ocean variability has increased substantially. In all cases, some property of the sediment is measured and climatic variability deduced. The most documented proxies for millennial changes in ocean climate and hydrography are: (1) changes in the noncarbonate sand-size (<2000 and $>63\,\mu\mathrm{m}$) fraction, the so-called iceberg rafted detrital (IRD) fraction; (2) changes in the $\delta^{18}O$ of planktonic and benthic foraminifera which reflect both changes in the global ice volume, temperature, and meltwater volume; (3) changes in the $\delta^{13}C$ of marine carbonates which is a measure of productivity and water mass history and is used to trace variations in the production and circulation patterns of bottom water; (4) changes in the composition of faunas or floras which reflect the response of the biota to oceanographic changes; and (5) changes in the geochemical properties of the inorganic shell of organisms, or bulk sediment, which can be calibrated against climatic variables, such as sea surface temperature (SST). Usually, more than one of these parameters is measured, or a ratio of, for example, lithics/lithics + foraminifera, is used to develop a scenario of oceanic climate variability (**Figure 1B**).

IRD (Heinrich) events

Heinrich's seminal paper (1988) on the occurrence, in cores off Portugal, of discrete IRD peaks during the last 60 000 years or so resulted in a wealth of data and hypotheses about 'Heinrich events'. It is now believed that 'armadas of icebergs' were released on a quasi-periodic basis into the North Atlantic, with the major source area being the Hudson Strait. Hudson Strait is a large, deep trough which drained a substantial fraction ($2\text{–}4 \times 10^6\,\mathrm{km}^2$) of the interior of the Laurentide Ice Sheet (**Figure 2**). In the Labrador Sea, and the areas south of Greenland and toward Europe, evidence for these armadas is dramatically visible in many parameters, but especially in the changes of the detrital carbonate content of the cores, derived from the erosion of the Paleozoic limestone that outcrops on the floors of Hudson Strait and Hudson Bay (**Figure 3**).

These dramatic sedimentological events have been termed H-0, H-1, etc. and have the following radiocarbon ages (years ago): H-0 = 10 000–11 000; H-1 = 14 500 ± ; H-2 = 20 500 ± ; H-3 = 27 000 ± ; H-4 = 34 000 ± (**Figures 1** and **3**). Older H-events, H-5 and H-6, lie beyond the limits of ^{14}C dating but have inferred ages of 48 000 and 60 000 years ago. Because of the ± error in the ^{14}C dates the duration of each of these IRD intervals is not well defined. Available dates indicate that they persisted for a few hundred to about 1000 years (**Figure 1B**) and have a quasi-periodic return interval averaging *c.* 6 ky.

Studies in the North Atlantic indicate that during H-events there are coeval changes in other parameters, with planktonic foraminiferal assemblages decreasing in numbers per gram but also becoming nearly entirely polar in composition. Benthic foraminifera show strongly decreased productivity. At the same time the stable oxygen isotopic composition suggests an increase in surface meltwater.

Controversy exists on the regional extent of H-events and the underlying mechanism(s) for discrete IRD events. Dating is clearly a critical issue as these millennial-scale events are of short duration and often date from times ($<20\,000$ years ago) when the errors of the radiocarbon dates are measured in one to several hundred years. In addition, efforts to correlate millennial-scale oceanic H-events with abrupt events on land (or in ice cores), face the problem of correcting the marine dates for both changes in the ocean reservoir correction and

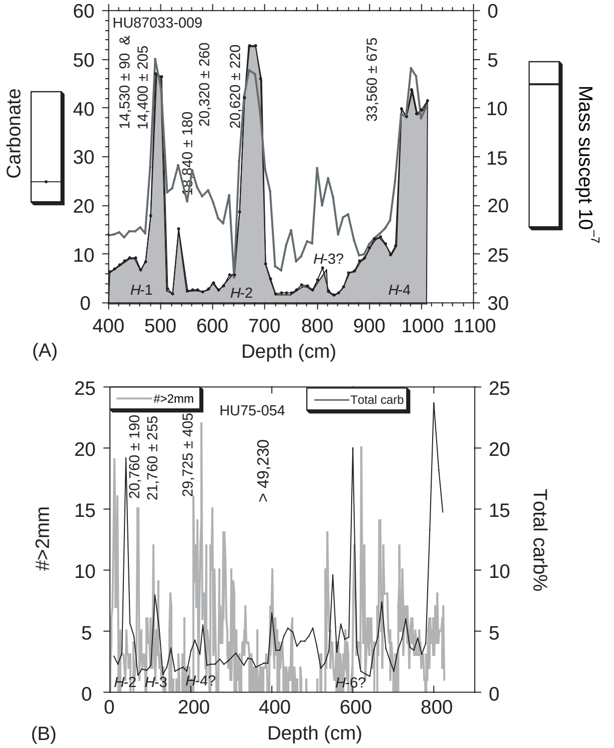

Figure 3 (A) Changes in the detrital carbonate content and magnetic susceptibility of core HU87033-009 from just north of the Hudson Strait outlet (see **Figure 2**). Note that the scale for mass magnetic susceptibility ($\times 10^{-7}\,m^3\,kg^{-1}$) is reversed because in this area the magnetite concentrations are diluted by the input of diamagnetic detrital carbonate. (B) Detrital carbonate and clasts $>2\,mm$ in HU75-054 from south of Davis Strait, Northwestern North Atlantic (**Figure 2**). Note that the agreement between detrital carbonate events (primarily a measure of North Atlantic Heinrich events) and coarse ice-rafted detritus is far from perfect.

^{14}C production rates. Thus ice core/ocean record correlations are often based on fitting the 'wiggles' of the proxies from the two systems.

The extent of IRD events coeval with the main North Atlantic belt of iceberg rafted materials (**Figure 2**) is a matter of debate. In the Nordic Seas, in the Labrador Sea, and in Baffin Bay, the IRD signal in cores is pervasive during the last glacial cycle and cannot be used *per se* to identify H-events (**Figure 3B**). In contrast, in the Labrador Sea H-events are easily distinguished by the dramatic increase in detrital carbonate during these abrupt events (**Figure 3A** and **B**). These data are not suprising; in areas close to ice margins the rafting of sediments in icebergs would be a persistent transport mechanism whereas the collapse or surge of a major outlet might be distinguished by an abrupt change in sediment provenance. It is also uncertain as to what extent small changes in IRD have any significance given the strong, stochastic nature of iceberg/sediment relationships.

The origins of these millennial-scale changes in ice-sheet dynamics is considered to be attributable to either inherent glaciological mechanisms associated with changes at the bed of these former ice sheets, or alternatively researchers have argued that they represent climate forcing. The main issue of concern for glaciologists is how atmospheric processes could translate to the bed of large ice sheets at a rate compatible with millennial scale variations. No plausible mechanism has been discovered. On the other-hand, if coeval H-events are seen outside the North Atlantic, which has been suggested, then mechanisms are needed to transfer the process from a regional scale to a global scale.

Two mechanisms have been invoked. They are not mutually exclusive. In the first scenario it is posited that a collapse of the North American Ice Sheet during an H-event causes a rapid rise in sea level of 1–5 m, which then triggers instabilities in other ice-sheet margins which have advanced toward the shelf break (in areas such as Norway, Greenland, Iceland). As yet it is unclear whether these events around the North Atlantic affected the grounded margins of the Antarctic Ice Sheet and the West Antarctic Ice Sheet in particular. In the second scenario, the collapse of the Northern Hemisphere ice sheets, or the Laurentide (North American) ice sheet in particular would result in the transport of large volumes of fresh water, in the form of icebergs and basal meltwater, to the North Atlantic. Isotopic changes in the $\delta^{18}O$ of planktonic foraminifera certainly occur during H-events (although foraminifera often disappear from the sediment during H-events, hence detailed records are sparse) and indicate that $\delta^{18}O$ values get lower, indicating the presence of a surface, low salinity layer. If these waters are advected toward sites of vertical convection in the North Atlantic then both theory and observations indicate that this process will turn-off or curtail the global Thermohaline Circulation. Thus the next question is whether sites beyond the normal limits of iceberg rafting and direct glacial impact show any evidence of millennial scale climate oscillations in either the surface or deep waters.

Other Millennial-scale Proxies

A variety of proxy data from deep-sea sediment drifts in the western North Atlantic, south of 35°N (**Figure 2**), indicate substantial, millennial-scale changes in the deep-ocean (**Figure 1A, C**). Changes in the $CaCO_3$ content of the sediment reflect the integration of carbonate production in surface waters, carbonate dissolution, resuspension and transport of continental margin sediments, and dilution with glacially and fluvially derived terrigenous sediments from the Canadian Maritimes and Eastern Canadian Arctic. Core GPC-9 was taken from a water depth of 4758 m on the Bahama Outer Ridge. The $CaCO_3$ record spectacularly captures oscillations in this proxy, which range over 48%, from lows during marine oxygen isotope stages (OS) #2 and 4 of ~2% to peaks during OS 5 of *c.* 50% (**Figure 1A, C**). It was also shown that these oscillations were also evident in the stable isotopic composition of foraminifera, although the isotopic changes tended to lead the carbonate fluctuations by 1000 years or so during carbonate event d. Changes in the $\delta^{13}C$ may be linked with changes in the thermohaline circulation, such that a significant reduction in the formation of North Atlantic Deep Water (NADW) is indicated by low $\delta^{13}C$ in two benthic foraminifera genera.

More recent work has concentrated on the events during OS #3 (**Figure 1**) as this was a period of extreme and abrupt oscillations in the Greenland ice core records. This interval includes Heinrich events 3, 4, and 5 (i.e., between ~31 600 and 47 800 calendar years ago (**Figure 1B**). Variations in $\delta^{13}C$ of planktonic foraminifera along a transect from the south of Iceland (*c.* 60°N) to the Ceara Rise (*c.* 5°N) (**Figure 2**) have been examined. Cores from different water depths along the transect were used to reconstruct changes in water mass on millenial timescales. A critical question is the relationship between changes in the deep-sea circulation and ventilation and H-events. Is there a cause and effect relationship such that H-events result in a response in ocean circulation? Because these sites are outside the IRD belt of the North Atlantic, the correlation between actual IRD or carbonate-rich H-events (e.g., **Figure 3**) and ocean geochemical responses relies on the quality of the chronology. Within OS #3 the errors on acceleration mass spectrometry ^{14}C dates are frequently between ±300 and ±500 years, hence the issue of a direct correlation to events lasting a mere 1000 years is of concern. However, the $\delta^{13}C$ records from the Ceara Rise indicate that cold, relatively fresh Antarctic Bottom Water (AABW, lower $\delta^{13}C$), which underlies the warmer and saltier North Atlantic Deep Water (NADW, higher $\delta^{13}C$), thickened by a factor of two. The thickening of the AABW at the site began 'several thousands of years' prior to each H-event and extended 'several thousand years' after each event. These intervals of expanded AABW were times of reduced NADW production. These intervals of reduced NADW production and associated reduction in the thermohaline circulation, cannot be directly caused by ice sheet collapse and the presence of a freshwater cap over the northern North Atlantic.

Further, in a core from the Bermuda Rise (near GPC-9) (**Figure 2**), reconstructed SST fluctuations of 2–5°C have been shown. These SST estimates could be mapped directly onto the $\delta^{18}O$ oscillations from the ice cores at the Greenland Summit.

Research has tended to focus on abrupt changes during the various intervals of the last glacial interval, essentially OS #5d to #2. A critical question for society is whether such rapid millennial-scale oscillations continued during the 'postglacial' or Holocene period of the last 10 000 radiocarbon years (about 12 300 calendar years), and if so were they too associated with changes in the thermohaline circulation and episodic ice-rafting events? In general, data from the Greenland ice cores indicate that climatic variability was substantially reduced during the Holocene. Temperature reconstructions from borehole and isotopic measurements indicate that temperatures at the summit of the ice sheet warmed dramatically by 16°C at the onset of the Holocene. Over the last 10 000 years there have been temperature variations of *c.* 2–3°C, and in the last 5000 years these are superimposed on a gradual, long-term temperature decrease. Based on the chronology of Holocene glacial readvances, a 2500 ± year cycle has been advocated.

It is only in the last few years or so that researchers in the marine community have focused on producing high-resolution records from this most recent interval of earth's history. Cores have often been selected that have sufficiently high rates of sediment accumulation that sampling can resolve multicentury – even multidecadal-scale events. There is a growing body of evidence that suggests that there has been a recurring, millennial-scale 1400 ± year 'beat' during the Holocene. Cycles with this periodicity have been reported from a variety of sedimentary archives including silt size (as a measure of current speed), sediment color, and the amount and composition of the sand fraction. Although the 1400 year cycles have been attributed to iceberg rafting events, their magnitude in the records is not remotely at the scale of the Heinrich events. The IRD events during the Holocene have been dated at *c.* 300 (? Little Ice Age), 1400, 2800, 4300, 5900, 8200, and 9500 ± calendar years.

Discussion: Importance and Mechanisms

In the 1970s and 1980s a common view of the global climate system on scales from 1 to 10^6 years was that there were systematic changes associated with the Milankovitch orbital variations which effected insolation. Evaluation of changes in the global ice volume indicated dominant periodicities of 41 000 and *c.* 20 000 years, and in the last 0.7 million years a 100 000-year cycle became evident. At higher frequencies the spectra of climatic variability was essentially blank between 20 000 years and the 22 year sunspot cycle. This absence of recurring periodicities suggested that global climate change within this range had no obvious or repetitive forcing function. The advent of the successful ice-coring programs, especially the Greenland Ice Sheet boreholes, and the subseqent development of well-dated, multiproxy records of the atmosphere, led to a search for recurring frequencies between 1/20 000 and 1/22 cycles per year. This analysis suggested that there is a 6000–7000 year periodicity which is approximately the same as the interval between the successive Heinrich events. Because of the largely unknown errors connected with the value of the ocean reservoir correction, and the conversion from radiocarbon years to sidereal years, the spacing between H-0 and H-4 was *c.* 5000, 8000, 7000, and 8000 years with uncertainities of several hundred years. However, each H-cycle was composed of several higher-frequency events, the Dansgaard–Oeschger (D–O) cycles, which had a recurrence interval of around 2000 years. In detailed records from cores in the North Atlantic, a series of D–O events are bundled with bounding H-events. These 'packages' show an overall saw-tooth decrease in warm surface water indicators over the course of a cycle, with a final abrupt and extreme minimum which marks the onset of an H-event. This was rapidly followed by a dramatic rise in the warm-water proxies. Broecker referred to this pattern as a 'Bond Cycle'. The prevailing wisdom calls for these oscillations to be associated with changes in the thermohaline circulation, but there is the 'chicken or egg' syndrome. Changes in the thermohaline circulation are usually associated with changes in the saltiness of the surface waters. Thus the dramatic collapse of a large ice sheet, and the subsequent export of fresh water in the form of meltwater plumes and icebergs, is a legitimate mechanism for curtailing convective over-turning at sites in the northern North Atlantic.

An important question, presently unanswered, then becomes how these changes are transmitted rapidly and at the millenial-scale, synchronously through the atmosphere (to account for the observed rapid changes in ice sheet isotopes and precipitation chemistry), and within the oceans. There are several lines of evidence to suggest that one way in which the ocean circulation compensates for changes in the 'deep' thermohaline circulation is by the increased production of what has been termed 'glacial intermediate water.'

There is a dramatic decrease in the variability of most proxies for climate in ocean sediments over the last 11 000 cal years. H- and D–O events characterize marine oxygen isotope stages #2, 3, and 4 (**Figure 1**) when the earth was marked by extensive glaciation and sea levels were lowered between 40 and 110 m. High-resolution sampling of marine cores from deep ocean basins and continental margins which span one to several thousand of years indicate that changes in oceanography have taken place at millennial timescales over the present interglacial period.

A key question is whether all proxies will record the same oscillations? The notion that there are thresholds in the climate system suggests that not all events may be archived in marine sedimentary records. An example is the Holocene ice rafting of sediments. In some parts of the world oceans measurable quantities of sediment could be rafting to ice-distal locations on and in sea ice. However, the sediment burden in sea ice is relatively light and, furthermore, the thickness of a typical multiyear pan of sea ice is measured in meters to a few tens of meters versus hundreds of meters for true icebergs. Hence, melting and erosion of sea ice results in a limited transport of sea ice rafted sediment when compared to iceberg rafting. Most of the North Atlantic's margins and offshore basins have seen a massive reduction in IRD following the retreat and disappearance of late Quaternary ice sheets (**Figures 2** and **4**). In todays world (**Figure 4**) the distribution of IRD-rich sediments is primarily restricted to the Greenland shelves and the eastern Canadian Arctic (Baffin Island and Labrador) margins, therefore even small traces of sand-size minerals distal to these areas may indicate intervals of iceberg rafting. However, the threshold in question is the presence of tidewater calving glaciers in the Greenland fiords. Observations from Greenland indicate that the ice sheet was well-behind its present margin by 6000 years ago and probably by 7000–8000 years ago. Even on the East Greenland margin, which today is 'well traveled' by icebergs, sediments deposited between 6000 and 8000 years ago are largely devoid of IRD, whereas between 5000 and 6000 years ago the iceberg rafting of coarse, clastic sediments becomes a pervasive depositional process.

Modern observations, however, do indicate that the production of Intermediate Atlantic Water is sensitive to modern-day atmospheric and oceano-

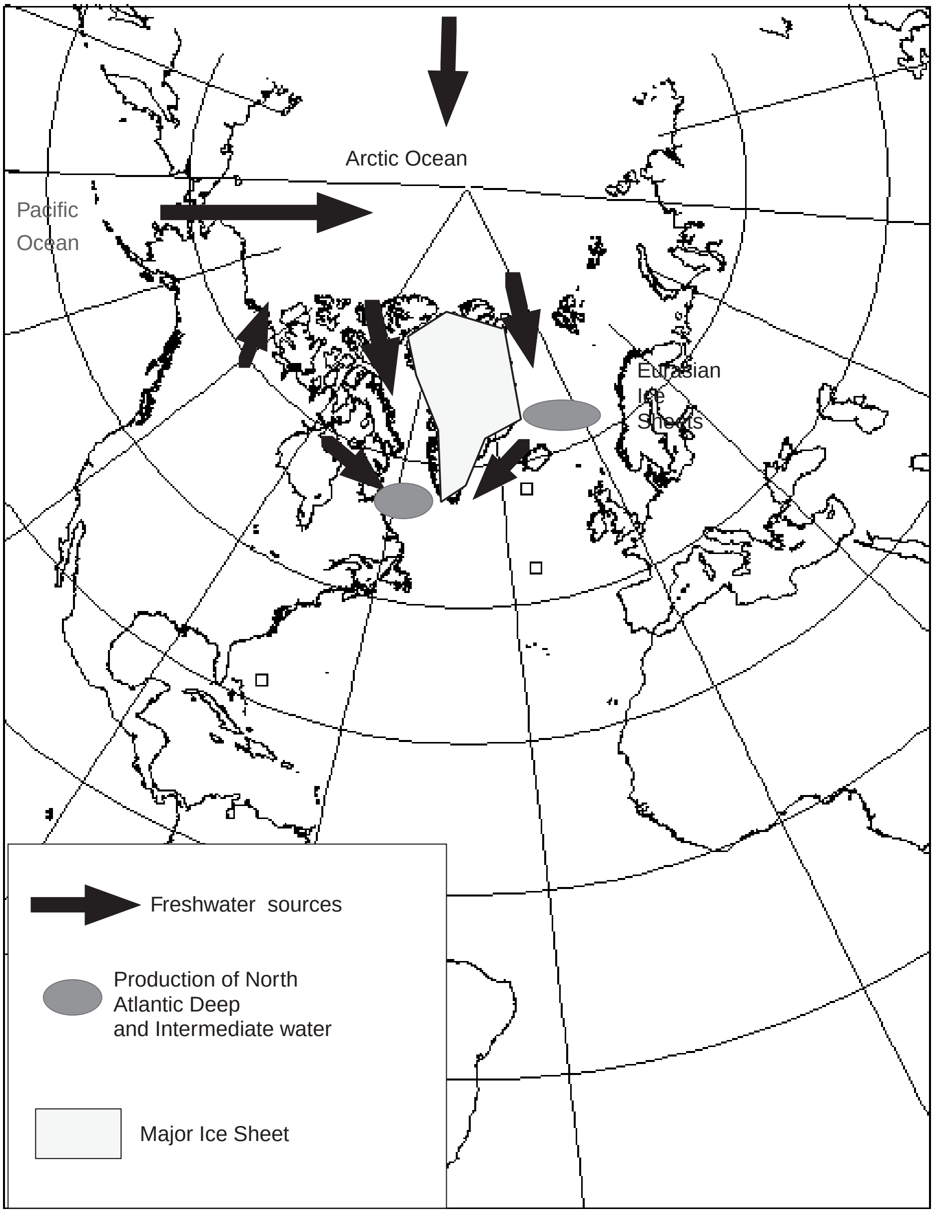

Figure 4 Major sources of salinity events and location of convection areas in the North Atlantic during the present 'interglacial' world. Sources include the influx of fresher water from the Pacific Ocean via the Bering Strait, river run-off into the Arctic Ocean, and the export of sea-ice from the Arctic Ocean via Fram Strait and the Canadian High Arctic Channels. Tidewater calving margins around the Greenland Ice Sheet lead to the calving of about 350 km^3 of ice per year.

graphic processes. The great salinity anomaly of the late 1960s and early 1970s (depending on location) was the result of an excess freshwater output from the Arctic Ocean (as sea ice) (**Figure 4**). This pool of relatively fresh, surface water, caused dramatic cooling of the water column off North Iceland (by 5°C), and as it moved into the Labrador Sea it caused a cessation in convective overturning. This resulted in a temperature drop of ~2°C on the west Greenland and Canadian margins.

Because another salinity anomaly occurred in the early 1980s, this time sourced from the Hudson Bay/Labrador Sea region, there certainly appear to be mechanisms within the present Climate System that are capable of generating rather severe and abrupt oceanographic changes. The question is whether the processes responsible for multidecadal climatic variability can be scaled-up, so that the processes persist and produce millennial oscillations in ocean records.

Conclusions

Millennial-scale changes are becoming an accepted reality. Initial research concentrated on the massive changes associated with the discharge of sediments and water into the North Atlantic Ocean during the last glacial cycle (marine oxygen isotope stages #2–5) (**Figures 1, 2** and **3**). However, high-resolution studies of our deglacial world (**Figure 4**) appear to indicate that similarly spaced but subdued events persist but with very diferent boundary conditions. A number of publications have also demonstrated that millennial-scale changes in various proxy records are a feature of ocean sediments over at least the last 500 000 years.

The work from tropical and subtropical sites (**Figure 2**) indicates that Heinrich events have manifestations in ocean reconstructions which belie a simple association with ice sheet instabiliy and collapse. It is far from clear how oceanographic and atmospheric changes are transmitted to the bed of large ice streams, and there is indeed disagreement as to whether the collapse of Northern Hemisphere ice sheets (**Figure 2**) was regionally coeval or whether the collapses are linked temporally by a mechanism, such as rapid changes in relative sea level. It has, however, been observed that the routing of fresh water (**Figure 4**) can have dramatic effects, even in the present world, and the key may well lie in a better understanding of the role of the ocean thermohaline circulation system in the global climate system.

See also

Cenozoic Climate – Oxygen Isotope Evidence. Thermohaline Circulation.

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MINERAL EXTRACTION, AUTHIGENIC MINERALS

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Introduction

The extraction of marine mineral resources represents a worldwide industry of just under two billion dollars per year. There are approximately a dozen