See also

Continuous Plankton Recorders. Fisheries and Climate. International Organizations. Law of the Sea. Maritime Archaeology. Primary Production Distribution. Primary Production Methods. Primary Production Processes.

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HOLOCENE CLIMATE VARIABILITY

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Introduction

Until a few decades ago it was generally thought that significant large-scale global and regional climate changes occurred at a gradual pace within a timescale of many centuries or millennia. Climate change was assumed to be scarcely perceptible during a human lifetime. The tendency for climate to change abruptly has been one of the most surprising outcomes of the study of Earth history. In particular, paleoceanographic records demonstrate that our present interglacial, the Holocene (the last ~10 000 years), has not been as climatically stable as first thought. It has been suggested that Holocene climate is dominated by millennial-scale variability, with some authorities suggesting that this is a 1500 year cyclicity. These pronounced Holocene climate changes can occur extremely rapidly, within a few centuries or even within a few decades, and involve regional-scale changes in mean annual temperature of several degrees Celsius. In addition, many of these Holocene climate changes are stepwise in nature and may be due to thresholds in the climate system.

Holocene decadal-scale transitions would presumably have been quite noticeable to ancient civilizations. For instance, the emergence of crop agriculture in the Middle East corresponds very closely with a sudden warming event marking the beginning of the Holocene, and the widespread collapse of the first urban civilizations, such as the Old Kingdom in Egypt and the Akkadian Empire, coincided with a cooling event at around 4300 BP. In addition, paleo-records from the late Holocene demonstrate the possible influence of climate change on the collapse of the Mayan civilization (Classic Period), while Andean ice core records suggests that alternating wet and dry periods influenced the rise and fall of coastal and highland cultures of Ecuador and Peru.

It would be foolhardy not to bear in mind such sudden stepwise climate transitions when considering the effects that humans might have upon the present climate system, via the rapid generation of greenhouse gases for instance. Judging by what we have already learnt from Holocene records, it is not improbable that the system may gradually build up over hundreds of years to a 'breaking point' or threshold, after which some dramatic change in the system occurs over just a decade or two. At the threshold point, the climate system is in a delicate and somewhat critical state. It may take only a relatively minor 'adjustment' to trigger the transition and tip the system into abrupt change.

This article summarizes the current paleoceanographic records of Holocene climate variability and the current theories for their causes. Concentrating on records that cover a significant portion of the Holocene. The discussion is limited to centennial–millennial-scale variations. **Figure 1** illustrates the Holocene and its climate variability in context of

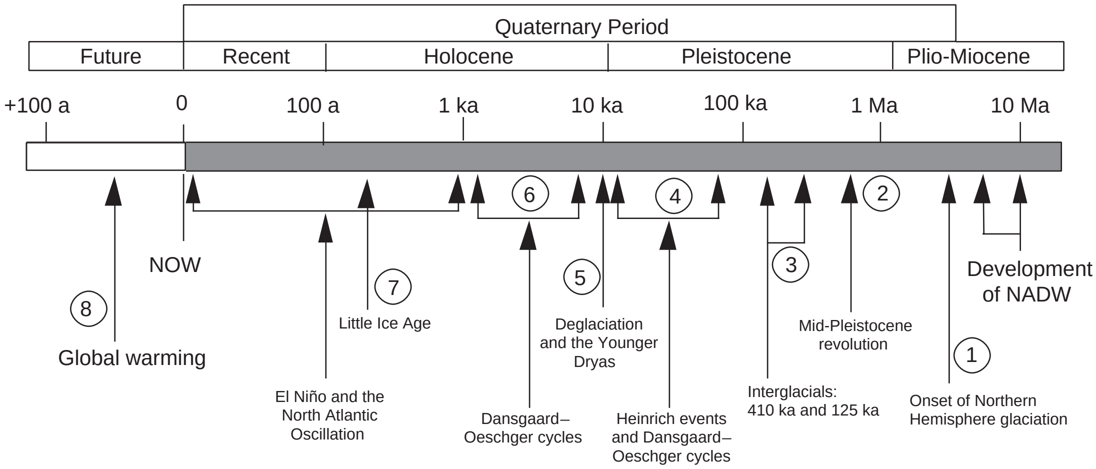

Figure 1 Log time scale cartoon, illustrating the most important climate events in the Quaternary Period. (a, ka, Ma, refer to years ago.) (1) Onset of Northern Hemisphere Glaciation (3.2–2.5 Ma), ushering in the strong glacial–interglacial cycles which are characteristic of the Quaternary Period. (2) Mid-Pleistocene Revolution when the dominant periodicity of glacial–interglacial cycles switched from 41 000 y, to every 100 000 y. The external forcing of the climate did not change; thus, the internal climate feedback's must have altered. (3) The two closest analogues to the present climate are the interglacial periods at 420 000 to 390 000 years ago (oxygen isotope stage 11) and 130 000 to 115 000 years ago (oxygen isotope stage 5e, also known as the Eemian). (4) Heinrich events and Dansgaard–Oeschger cycles (see text). (5) Deglaciation and the Younger Dryas events. (6) Holocene Dansgaard–Oeschger cycles (see text). (7) Little Ice Age (AD 1700), the most recent climate event that seems to have occurred throughout the Northern Hemisphere. (8) Anthropogenic global warming.

the major global climatic changes that have occurred during the last 2.5 million years. Short-term variations such as the North Atlantic Oscillation and the El Niño-Southern Oscillation will not be discussed.

The Importance of the Oceans and Holocene Paleoceanography

Climate is created from the effects of differential latitudinal solar heating. Energy is constantly transferred from the equator (relatively hot) toward the poles (relatively cold). There are two transporters of such energy – the atmosphere and the oceans. The atmosphere responds to an internal or external change in a matter of days, months, or may be a few years. The oceans, however, have a longer response time. The surface ocean can change over months to a few years, but the deep ocean takes decades to centuries. From a physical point of view, in terms of volume, heat capacity and inertia, the deep ocean is the only viable contender for driving and sustaining long-term climate change on centennial to millennial timescales.

Since the process of oceanic heat transfer largely regulates climate change on longer time-scales and historic records are too short to provide any record of the ocean system prior to human intervention, we turn to marine sediment archives to provide information about ocean-driven climate change. Such archives can often provide a continuous record on a variety of timescales. They are the primary means for the study and reconstruction of the stability and natural variability of the ocean system prior to anthropogenic influences.

One advantage of marine sediments is that they can provide long, continuous records of Holocene climate at annual (sometimes intraannual) to centennial time-resolutions. However, there is commonly a trade-off between temporal and spatial resolution. Deep-ocean sediments usually represent a large spatial area, but sedimentation rates in the deep-ocean are on average between 0.002 and $0.005\,\mathrm{cm\,y^{-1}}$, with very productive areas producing a maximum of $0.02\,\mathrm{cm\,y^{-1}}$. This limits the temporal resolution to a maximum of 200 years per cm ($50\,\mathrm{y\,cm^{-1}}$ for productive areas). Mixing by the process of bioturbation will reduce the resolution further.

On continental shelves and in bays and other specialized sediment traps such as anoxic basins and fiords, sedimentation rates can exceed $1\,\mathrm{cm\,y^{-1}}$ providing temporal resolution of over $1\,\mathrm{y\,cm^{-1}}$. More local conditions are recorded in laminated marine sediments formed in anoxic environments, where biological activity can not disturb the sediments. For example, Pike and Kemp (1997) analysed annual and intraannual variability within the Gulf of

California from laminated sediments containing a record of diatom-mat accumulation. Time series analysis highlighted a decadal-scale variability in mat-deposition associated with Pacific-wide changes in surface water circulation, suggested to be influenced by solar-cycles. In addition, anoxic sediments from the Mediterranean Ridge (ODP Site 971) reveal seasonal-scale variability during the late Quaternary from a laminated diatom-ooze sapropel. Pearce *et al.*, (1998) inferred changes in the monsoon-related nutrient input to the Mediterranean Basin via the Nile River as the main cause of the variations in the laminated sediments, which suggests a wide influence of changes in seasonality. Other potentially extremely high-resolution studies will come from Saanich Inlet, a Canadian fiord and Prydz Bay in Antarctica, sites recently drilled by the Ocean Drilling Program.

However, the main drawback to such high-resolution locations is that they contain highly localized environmental and climate information. An additional problem associated mainly with continental margins is reworking, erosion, and redistribution of the sediment by mass density flows such as turbidities and slumps. Hence we concentrate on wider-scale records of Holocene climate change.

Holocene Climatic Variability

Initial studies of the Greenland ice core records concluded the absence of major climate variation within the Holocene. This view is being progressively eroded, particular in the light of new information being obtained from marine sediments (**Figure 2**). Long-term trends indicate an early to mid-Holocene climatic optimum with a cooling trend in the late Holocene. Superimposed on this trend are several distinct oscillations or climatic cooling steps that appear to be of widespread significance (see **Figure 2**), the most dramatic of which occurred 8200, 5500, and 4400 years ago and between AD 1200 and AD 1650.

The event 8200 years ago is the most striking and abrupt, leading to widespread cool and dry conditions lasting perhaps 200 years, before a rapid return to climates warmer and generally moister than at present. This event is noticeably present in the GISP2 Greenland ice cores, from which it appears to have been about half as severe as the Younger Dryas to Holocene transition. Marine records of North African to Southern Asian climate suggest more arid conditions involving a failure of the summer monsoon rains. Cold and/or arid conditions also seem to have occurred in northernmost South America, eastern North America and parts of north-west Europe.

In the middle Holocene approximately 5500–5300 years ago there was a sudden and widespread shift in precipitation, causing many regions to become either noticeably drier or moister. The dust and sea surface temperature records off north-west Africa show that the African Humid Period, when much of subtropical West Africa was vegetated,

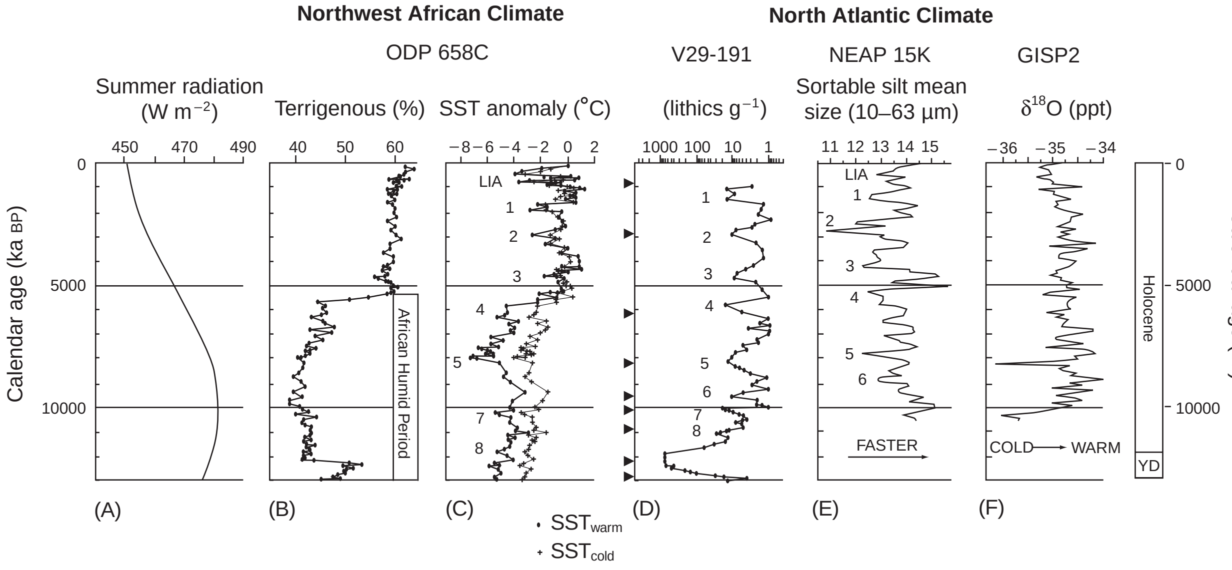

Figure 2 Comparison of summer insolation for 65°N with north-west African climate (deMenocal *et al.*, 2000) and North Atlantic climate (V29-191, Bond *et al.*, 1997; NEAP 15 K, Bianchi and McCave, 1999; GISP2, O'Brien *et al.*, 1996). Note the similarity of events labeled 1 to 8 and the Little Ice Age (LIA).

lasted from 14 800 to 5500 years ago and was followed by a 300 year transition to much drier conditions (de Menocal *et al.*, 2000). This shift also corresponds to the decline of the elm (*Ulmus*) in Europe about 5700, and of hemlock (*Tsuga*) in North America about 5300 years ago. Both vegetation changes were initially attributed to specific pathogen attacks, but it is now thought they may have been related to climate deterioration. The step to colder and drier conditions in the middle of an interglacial period is analogous to a similar change that is observed in records of the last interglacial period referred to as Marine Oxygen Isotope Stage 5e (Eemian).

There is also evidence for a strong cold and arid event occurring about 4400 years ago across the North Atlantic, northern Africa, and southern Asia. This cold, and arid event coincides with the collapse of a large number of major urban civilizations, including the Old Kingdom in Egypt, the Akkadian Empire in Mesopotamia, the Early Bronze Age societies of Anatolia, Greece, Israel, the Indus Valley civilization in India, the Hilmand civilization in Afganistan, and the Hongshan culture of China.

Little Ice Age (LIA)

The most recent Holocene cold event is the Little Ice Age (see **Figures 2** and **3**). This event really consists of two cold periods, the first of which followed the Medieval Warm Period (MWP) that ended ~ 1000 years ago. This first cold period is often referred to as the Medieval Cold Period (MCP) or LIAb. The MCP played a role in extinguishing Norse colonies on Greenland and caused famine and mass migration in Europe. It started gradually before AD 1200 and ended at about AD 1650. This second cold period, may have been the most rapid and the largest change in the North Atlantic during the Holocene, as suggested from ice-core and deep-sea sediment records. The Little Ice Age events are characterized by a drop in temperature of 0.5–1°C in Greenland and a sea surface temperature falls of 4°C off the coast of west Africa and 2°C off the Bermuda Rise (see **Figure 3**).

Holocene Dansgaard-Oeschger cycles

The above events are now regarded as part of the millennial-scale quasiperiodic climate changes characteristic of the Holocene (see **Figure 2**) and are thought to be similar to glacial Dansgaard–Oeschger (D/O) cycles. The periodicity of these Holocene D/O cycles is a subject of much debate. Initial analysis of the GISP2 Greenland ice core and North Atlantic sediment records revealed cycles at approximately the same 1500 (± 500)-year rhythm as that found within the last glacial period. Subsequent analyses have also found a strong 1000-year cycle and a 550-year cycle. These shorter cycles have also been recorded in the residual δ^{14}C data derived from dendrochronologically calibrated bidecadal tree-ring measurements spanning the last 11 500 years. In general, during the coldest point of each of the millennial-scale cycles shown in **Figure 2**, surface water temperatures of the North Atlantic were about 2–4°C cooler than during the warmest part.

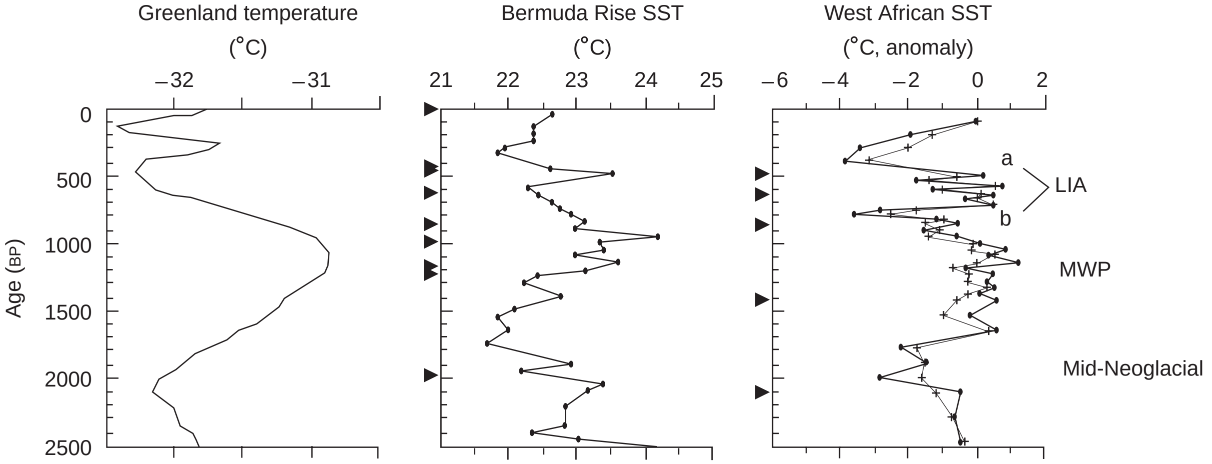

Figure 3 Comparison of Greenland temperatures, the Bermuda Rise sea surface temperatures (SST) (Keigwin, 1996), and west African and a sea surface temperature (deMenocal *et al.*, 2000) for the last 2500 years. LIA = Little Ice Age; MWP = Medieval Warm Period. Solid triangles indicate radiocarbon dates.

One cautionary note is that Wunsch has suggested a more radical explanation for the pervasive 1500-year cycle seen in both deep-sea and ice core, glacial and interglacial records. Wunsch suggests that the extremely narrow spectral lines (less than two bandwidths) that have been found at about 1500 years in many paleo-records may be due to aliasing. The 1500-year peak appears precisely at the period predicted for a simple alias of the seasonal cycle sampled inadequately (under the Nyquist criterion) at integer multiples of the common year. When Wunsch removes this peak from the Greenland ice core data and deep-sea spectral records, the climate variability appears as expected to be a continuum process in the millennial band. This work suggests that finding a cyclicity of 1500 years in a dataset may not represent the true periodicity of the millennial-scale events. The Holocene Dansgaard–Oeschger events are quasi periodic, with different and possibly stochastic influences.

Causes of Millennial Climate Fluctuation during the Holocene

As we have already suggested, deep water circulation plays a key role in the regulation of global climate. In the North Atlantic, the north-east-trending Gulf Stream carries warm and relatively salty surface water from the Gulf of Mexico up to the Nordic seas. Upon reaching this region, the surface water has cooled sufficiently that it becomes dense enough to sink, forming the North Atlantic Deep Water (NADW). The ‘pull’ exerted by this dense sinking maintains the strength of the warm Gulf Stream, ensuring a current of warm tropical water into the North Atlantic that sends mild air masses across to the European continent. Formation of the NADW can be weakened by two processes. (1) The presence of huge ice sheets over North America and Europe changes the position of the atmospheric polar front, preventing the Gulf Stream from traveling so far north. This reduces the amount of cooling and the capacity of the surface water to sink. Such a reduction of formation occurred during the last glacial period. (2) The input of fresh water forms a lens of less-dense water, preventing sinking. If NADW formation is reduced, the weakening of the warm Gulf Stream causes colder conditions within the entire North Atlantic region and has a major impact on global climate. Bianchi and McCave, using deep-sea sediments from the North Atlantic, have shown that during the Holocene there have been regular reductions in the intensity of NADW (**Figure 2E**), which they link to the 1500-year D/O cycles identified by O’Brien and by Bond (1997). There are two possible causes for the millennial-scale changes observed in the intensity of the NADW: (1) instability in the North Atlantic region caused by varying freshwater input into the surface waters; and (2) the ‘bipolar seesaw’.

There are a number of possible reasons for the instability in the North Atlantic region caused by varying fresh water input into the surface waters:

- Internal instability of the Greenland ice sheet, causing increased meltwater in the Nordic Seas that reduces deep water formation.
- Cyclic changes in sea ice formation forced by solar variations.
- Increased precipitation in the Nordic Seas due to more northerly penetration of North Atlantic storm tracks.
- Changes in surface currents, allowing a larger import of fresher water from the Pacific, possibly due to reduction in sea ice in the Arctic Ocean.

The other possible cause for the millennial-scale changes is an extension of the suggested glacial intrinsic millennial-scale ‘bipolar seesaw’ to the Holocene. One of the most important finds in the study of glacial millennial-scale events is the apparent out-of-phase climate response of the two hemispheres seen in the ice core climate records from Greenland and Antarctica. It has been suggested that this bipolar seesaw can be explained by variations in the relative amount of deep water formation in the two hemispheres and heat piracy (**Figure 4**). This mechanism of altering dominance of the NADW and the Antarctic Bottom Water (AABW) can also be applied to the Holocene. The important difference with this theory is that the trigger for a sudden ‘switching off’ or a strong decrease in rate of deep water formation could occur either in the North Atlantic or in the Southern Ocean. AABW forms in a different way than NADW, in two general areas around the Antarctic continent: (1) near-shore at the shelf–ice, sea-ice interface and (2) in open ocean areas. In near-shore areas, coastal polynya are formed where katabatic winds push sea ice away from the shelf edge, creating further opportunity for sea ice formation. As ice forms, the surface water becomes saltier (owing to salt rejection by the ice) and colder (owing to loss of heat via latent heat of freezing). This density instability causes sinking of surface waters to form AABW, the coldest and saltiest water in the world. AABW can also form in open-ocean Antarctic waters; particularly in the Weddell and Ross seas; AABW flows around Antarctica and penetrates the North Atlantic, flowing under the less dense NADW. It also flows into the Indian and Pacific oceans, but the

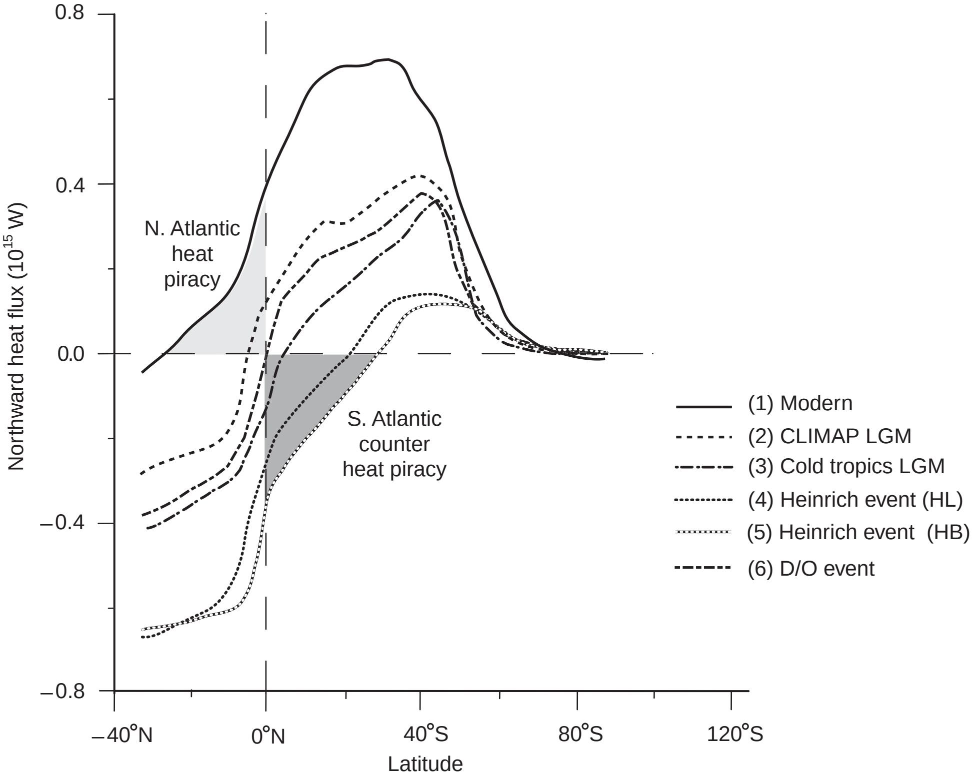

Figure 4 Atlantic Ocean poleward heat transport (positive indicates a northward movement) as given by the ocean circulation model (Seidov and Maslin, 1999) for the following scenarios: (1) present-day (warm interglacial) climate; (2) last glacial maximum (LGM) with generic CLIMAP data; (3) 'Cold tropics' LGM scenario; (4) a Heinrich-type event driven by the meltwater delivered by icebergs from decaying Laurentide ice sheet; (5) a Heinrich-type event driven by meltwater delivered by icebergs from decaying Barents Shelf ice sheet or Scandinavian ice sheet; (6) a general Holocene or glacial Dansgaard–Oeschger (D/O) meltwater confined to the Nordic Seas. Note that the total meridional heat transport can only be correctly mathematically computed in the cases of cyclic boundary conditions (as in Drake Passage for the global ocean) or between meridional boundaries, as in the Atlantic Ocean to the north of the tip of Africa. Therefore the northward heat transport in the Atlantic ocean is shown to the north of 30°S only.

most significant gateway to deep ocean flow is in the south-west Pacific, where 40% of the world's deep water enters the Pacific. Interestingly, Seidov and colleagues have shown that the Southern Ocean is twice as sensitive to meltwater input as is the North Atlantic, and that the Southern Ocean can no longer be seen as a passive player in global climate change. The bipolar seesaw model may also be self sustaining, with meltwater events in either hemisphere, triggering a train of climate changes that causes a meltwater event in the opposite hemisphere, thus switching the direction of heat piracy (**Figure 5**).

Conclusion

The Holocene, or the last 10 000 years, was once thought to be climatically stable. Recent evidence, including that from marine sediments, have altered this view, showing that there are millennial-scale climate cycles throughout the Holocene. In fact we are still in a period of recovery from the last of these cycles, the Little Ice Age. It is still widely debated whether these cycles are quasiperiodic or have a regular cyclicity of 1500 years. It is also still widely debated whether these Holocene Dansgaard–Oeschger cycles are similar in time and characteristic to those observed during the last glacial period. A number of different theories have been put forward for the causes of these Holocene climate cycles, most suggesting variations in the deep water circulation system. One suggestion is that these cycles are caused by the oscillating relative dominance of North Atlantic Deep Water and Antarctic Bottom Water. Holocene climate variability still has no adequate explanation and falls in the 'gap' of our knowledge between Milankovitch forcing of ice ages and rapid variations such as El Niño and the North Atlantic Oscillation (**Figure 6**). Future research is essential for understanding these climate cycles so that we can better predict the climate response to anthropogenic 'global warming.'

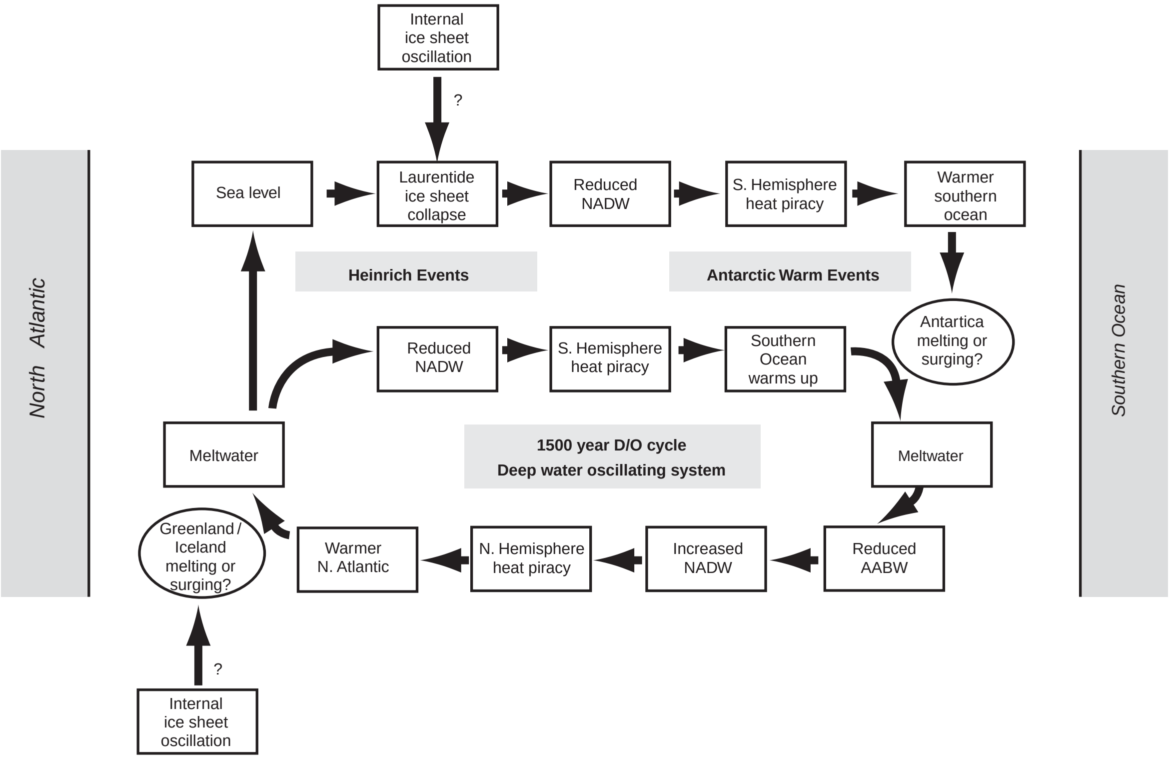

Figure 5 Possible deep water oscillatory system explaining the glacial and interglacial Dansgaard–Oeschger cycles. Additional loop demonstrates the possible link between interglacial Dansgaard–Oeschger cycles and Heinrich events.

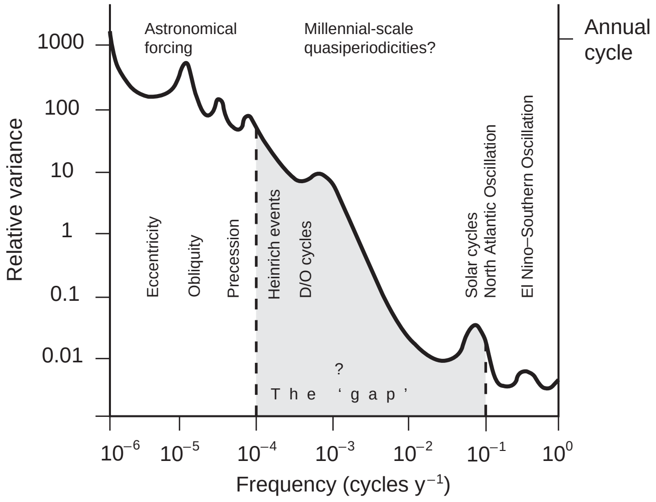

Figure 6 Spectrum of climate variance showing the climatic cycles for which we have good understanding and the 'gap' between hundreds and thousands of years for which we still do not have adequate understanding of the causes.

See also

Antarctic Circumpolar Current. Calcium Carbonates. Cenozoic Oceans – Carbon Cycle Models. Current Systems in the Atlantic Ocean. Deep Convection. Deep-sea Drilling Methodology. Deep-sea Drilling Results. Millenial Scale Climate Variability. Ocean Circulation. Ocean Subduction. Ocean Margin Sediments. Paleoceanography: Overview. Sediment Chronologies. Thermohaline Circulation. Water Types and Water Masses.

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HUMIDITY

See **EVAPORATION AND HUMIDITY**

HYDROTHERMAL VENT BIOTA

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On 17 February 1977, the deep-submergence vehicle *Alvin* descended 2500 m to the crest of the Galapagos Rift spreading center to first visit an ecosystem that would forever change our view of life in the deep sea. Cracks and crevices in the ocean floor were emanating fluids with temperatures up to 17°C. None of the bizarre organisms clustering around these 'hydrothermal vents' had ever been encountered; they comprised new species, genera, families, superfamilies, and bizarre 'tubeworms,' up to 2 m long, which were subsequently placed in a new phylum (Vestimentifera) (**Figure 1**). Since the Galapagos Rift discovery, numerous hydrothermal vent sites have been found throughout the world's oceans and over 500 new species have been described from these regions. **Figure 2** depicts many of the major hydrothermal systems from which organisms have been collected to date. Fluids with temperatures as high as 403°C exit from polymetallic sulfide chimneys in many of these regions (**Figure 3**).