Synthesis of the Nature and Causes of Rapid Climate Transitions During the Quaternary

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The last few million years have been punctuated by many abrupt climate transitions many of them occurring on time-scales of centuries or even decades. In order to better understand our current climate system we need to understand how these past climate transitions occurred. In this study we examine and review the paleoclimate proxies and modeling results for each of the key climate transitions in the Quaternary period. These are identified as: 1) Onset of Northern Hemisphere Glaciation (ONHG), 2) glacial-interglacial cycles, 3) Mid-Pleistocene Revolution (MPR), 4) Heinrich events and glacial Dansgaard-Oeschger (D-O) cycles, 5) last glacial-interglacial transition (LGIT) and the Younger Dryas, 6) interglacial climate transition such as the Intra-Eemian cold event and Holocene D-O cycles. For each climate transition the current theories of causation are critically examined and our own synthesis based on current knowledge is put forward. Most of these transitions appear to be threshold changes where by external forcing combined with internal feedbacks leads to a change in the state of global climate. We argue that bifurcation within the climate system means that it is easier for the global climate to go through these thresholds than it is to return to its previous state. Although this does not necessarily make climate change irreversible, it may provide a mechanism, which facilitates the locking of the climate system into a new equilibrium state. We suggest that the evidence indicates that long-term climate change occurs in sudden jumps rather than incremental changes; which does not bode well for the future.

INTRODUCTION

Rapidity of Global Climate Change

Until a few decades ago it was generally thought that significant large-scale global and regional climate changes occurred gradually over a time scale of many centuries or millennia. Hence the climate shifts were assumed to be

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scarcely perceptible during a human lifetime. The tendency of climate to change abruptly has been one of the most surprising outcomes of the study of earth history, especially from the polar ice core records for the last 150,000 years [e.g., *Taylor et al.* 1993; *Dansgaard et al.*, 1993; *Alley*, 2000]. Some and possibly most pronounced climate changes (involving, for example, a regional change in mean annual temperature of several degrees Celsius) occurred on a time scale of a few centuries, but frequently within a few decades, or even just a few years.

The decadal-time-scale transitions would presumably have been quite noticeable to humans living at such times [e.g., *deMenocal*, 2001]. For instance *Hodell et al.* [1995] and *Curtis et al.* [1996] consider the possible importance of climate change on the collapse of the Classic period of Mayan civilization. It has also been suggested that alternating wet and dry periods influenced the rise and fall of coastal and highland cultures of Ecuador and Peru [*Thompson and Mosley-Thompson*, 1987; *Thompson*, 1989; *Thompson et al.*, 1995]. The emergence of crop agriculture in the Middle East corresponds very closely with a sudden warming event marking the beginning of the Holocene [*Wright*, 1993], while the global collapse of the urban civilizations coincided with the deterioration of climate around 4,300 BP [*Peiser*, 1998; *Cullen et al.*, 2000]. On longer time scales, the evolution and migration of modern humans has also been linked to climatic changes in Africa [e.g., *de Menocal*, 1995; *Vrba et al.*, 1996; *Wilson et al.*, 2000]. These sudden stepwise climate transitions are also a disturbing scenario to be borne in mind when considering the effects that humans might have on the present climate system through the rapid generation of greenhouse gases. Judging by what we can learn from records of the past, conditions might gradually building to a 'break point' or threshold following which a dramatic change in the global climate system might occur over just a decade or two. The actual trigger for this transition, because of the threshold, may be quite innocuous. In this overview we summarize the current ideas on the causes of rapid climate changes during the last 2.5 million years, their impacts on the modern climate system and implications for our anthropogenic 'forcing' of the global climate system. In many cases we are still at the stage of speculating what may have been the underlying cause of these transitions and thus there is still a huge amount of work to be done in paleoclimatology.

Modes of Climate Change

Global climate changes are responses to external or internal forcing mechanisms. A good example of an external forcing mechanism is the changing orbital parameters which alter the net radiation budget of the Earth, while an example of an internal forcing mechanism is the carbon dioxide content of the atmosphere which modulates the greenhouse effect. We can abstract the way the global climate system responds to an internal or external forcing agent by examining four different scenarios:

Linear and synchronous response (Figure 1a). In this case the forcing produces a direct response in the climate system whose magnitude is in proportion to the forcing.

Muted or limited response (Figure 1b). In this case the forcing may be extremely strong, but the climate system in someway buffered and therefore has very little response.

Delayed or non-linear response (Figure 1c). In this case the climate system may have a slow response to the forcing or is in some way buffered at first. After an initial period then the climate system responds to the forcing but in a non-linear way.

Threshold response (Figure 1d). In this case initially there is no or very little response in the climate system to the forcing, however all the response takes place in a very short period of time in one large step or threshold. In many cases the response may be much larger than one would expect from the size of the forcing and this can be referred to as a response over-shoot.

Though these are purely theoretical models of how the climate system can respond they are important to keep in mind when reviewing global climate transitions. Moreover these scenarios can be applied to the whole range of spatial and temporal scales. This review hopefully illustrates how a study of paleoclimatology helps to distinguish between these possible scenarios and establishing how regional and global climate responded to different forcing mechanisms in the past. Examples of abrupt major climate transitions and cycles are reviewed, ranging from the initiation of Northern Hemisphere Glaciation and the start of the Quaternary, to the higher (on geological time scale) frequency climate changes that characterize the Holocene. Figure 2 shows on a the most important major climatic phenomena that occurred during the Quaternary period log time-scale. These phenomena are the main focus of the review.

An added complication when assessing the causes of climate changes is the possibility that climate thresholds contain bifurcations. This means the forcing required to go one way through the threshold is different from the reverse. This implies that once a climate threshold has occurred it is a lot more difficult to reverse it. This bifurcation of the climate system has been inferred from ocean models which mimic the impact of freshwater on deep-water formation in the North Atlantic [e.g., *Rahmstorf*, 1996]. However such an irregular relationship can be ap-

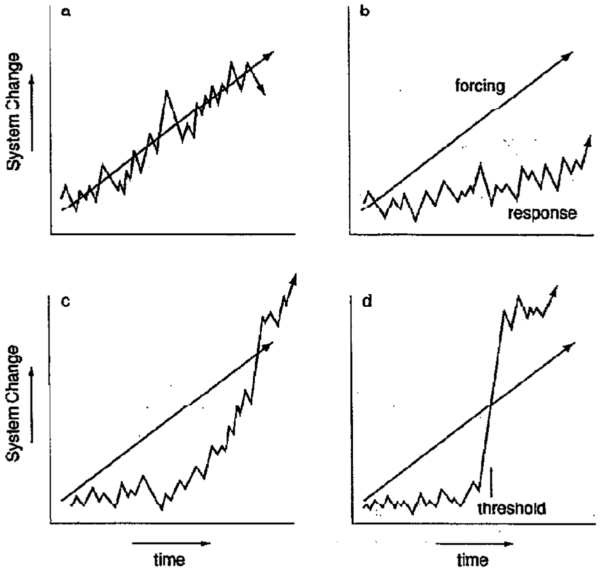

Figure 1. Schematic of the four alternative responses of the global climate system to internal or external forcing: a) Linear and synchronous response. In this case the forcing produces a direct response in the climate system whose magnitude is in proportion to the forcing. b) Muted or limited response. In this case the forcing may be extremely strong, but the climate system in someway buffered and therefore has very little response. c) Delayed or non-linear response. In this case the climate system may have a slow response to the forcing or is in some way buffered at first. After an initial period then the climate system responds to the forcing but in a non-linear way. d) Threshold response. In this case initially there is no or very little response in the climate system to the forcing, however all the response takes place in a very short period of time in one large step or threshold. In many cases the response may be much larger than one would expect from the size of the forcing and this can be referred to as a response overshoot.

plied to any forcing mechanism and the corresponding response of the global climate system. Figure 3 demonstrates this bifurcation of the climate system and shows that there can be different relationships between climate and the forcing mechanism, depending on the direction of the threshold. This is very common in natural systems for example in cases where inertia or the shift between different states of matter need to be overcome. Figure 3 shows that in case A and B the system is reversible, but in case C it is not. In case C the control variable must increase to more than it was in the previous equilibrium state to get over the threshold and return the system to it pre-threshold state. Let us consider this in terms of the salinity of the North Atlantic versus the production of North Atlantic Deep Water (NADW), as we know that adding more freshwater to the North Atlantic hampers the production of salty cold and hence heavy deep water. In Case A, changing the salinity of the North Atlantic has no effect on the amount of NADW produced. In Case B reducing the salinity reduces the production of NADW, however if the salt is replaced then the production of NADW returns to it previous, pre-threshold level. In case C, reducing the North Atlantic salinity reduces the production of NADW. However simply returning the salt does not return the NADW production to the normal level. Because of the bifurcation, a lot more salt has to be injected to bring back the NADW production to its previous level. It may be that the extra amount of salt required is not possible within the system and hence this makes the system theoretically irreversible. The major problems we face when looking at both past and future climate change whether a bifurcation may occur and whether evolution of the system is reversible (Figure 3).

When discussing the behavior of climatic forcing the response time of the different parts of the Earth climate system must also be considered. Figure 4 shows the response times of the different internal systems that vary from hundreds of millions of years to days. The complication is that all of these processes are constantly changing but at different rates. They will also have different responses to external or internal forcing as suggested in Figure 1. In this paper we review how the history of Quaternary climatic change has been influenced by a wide range of possible forcing mechanisms from the long term tectonic forcing to the much short human time scale changes in the atmospheric and ocean circulation patterns, the impacts of which could be detected within a human lifetime (Figure 4). The paper is arranged along a time-line starting with the onset of the Quaternary period and its characteristic great 'ice ages' [Wilson et al., 2000].

I. ONSET OF NORTHERN HEMISPHERE GLACIATION.

I.A. TIMING.

The earliest recorded onset of significant global glaciation during the last 100 Ma was the widespread continental glaciation of Antarctica at about 34 Ma [e.g., *Hambrey et al.*, 1991; *Breza and Wise*, 1992; *Miller et al.*, 1991; *Zachos et al.*, 1992; 1996; 1999; 2001]. In contrast the earliest recorded glaciation in the Northern Hemisphere is between 10 and 6 Ma [e.g., *Jansen et al.*, 1990; *Wolf and Thiede*; 1991; *Jansen and Sjøholm*, 1991; *ODP Leg 151*, 1994; *Wolf-Welling et al.*, 1995]. Marked expansion of continental ice sheets in the Northern Hemisphere was the

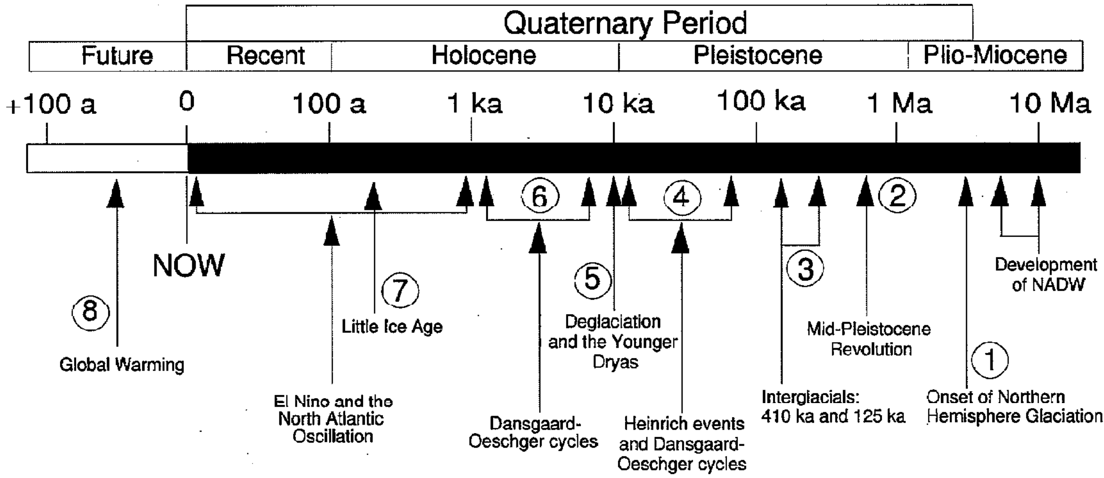

Figure 2. Log time-scale cartoon, illustrating the most important climate events identified by this study in the Quaternary Period [adapted from *Adams et al.*, 1999]. 1. Onset of Northern Hemisphere Glaciation (3.2 to 2.5 Ma) ushering in the strong glacial-interglacial cycles which are characteristic of the Quaternary Period. 2. Mid-Pleistocene Revolution when glacial-interglacial cycles switched from 41 ka, to every 100 ka. The external forcing of the climate did not change, thus, the internal climate feedback's must have altered. 3. The two closest analogs to the present climate are the interglacial periods at 420-390 ka (Oxygen isotope stage 11) and 130-115 ka (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 (1700 AD) the most recent climate event which seemed have occur throughout the Northern Hemisphere. 8. Anthropogenic Global Warming

culmination of a longer term, high latitude cooling, which began with this late Miocene glaciation of Greenland and the Arctic and continued through to the major increases in global ice volume around 2.5 Ma [*Prell*, 1984; *Keigwin*, 1986; *Ruddiman et al.*, 1986a and b; *Sarnthein and Tiedemann*, 1989; *Tiedemann et al.*, 1994].

Evidence from orbitally tuned Ocean Drilling Program records (Sites, 609, 610, 642, 644, 552, 882, 887] *Maslin et al.* [1998a] suggested that this long term cooling led to three key steps in the glaciation of the Northern Hemisphere (see Figure 5): a) Eurasian Arctic and Northeast Asia were glaciated at approximately 2.74 Ma, b) glaciation of Alaska at 2.70 Ma and c) the significant glaciation of the North East American continent at 2.54 Ma. Sea level changes, inferred from the benthic foraminiferal oxygen isotope records obtained from ODP Sites 659 [*Tiedemann et al.*, 1994] and 846 [*Shackleton et al.*, 1995, see Fig. 5] supports this and suggests that the two most important stages in the glaciation of the Northern Hemisphere were the maturing of the Eurasian-Northeast Asian ice sheets (oxygen isotope stage 110 or G6) and the proto-Laurentide ice sheet on the eastern North American continent (oxygen isotope stage 100). This step-like nature of the ice rafting records may, however, conceal a more gradual process of ice build-up, as revealed by the progressive ^{18}O enrichment of benthic isotope records [*Tiedemann et al.*, 1994; *Shackleton et al.*, 1995]. This is because the ice-rafting records indicate only when the continental ice sheets were mature enough to impinge on the adjacent oceans. Dramatic changes, however, are observed in each ocean basin when ice-rafting first occurs.

I.b. Possible Causes of the Onset of Northern Hemisphere Glaciation.

The predominant theories to explain the Onset of Northern Hemisphere Glaciation have focused on major tectonic events and their modification of both atmospheric and ocean circulation [*Hay*, 1992; *Raymo*, 1994a; *Maslin et al.*, 1998a]. For example the uplift and erosion of the Tibetan-Himalayan plateau [*Ruddiman and Raymo*, 1988; *Raymo*, 1991, 1994b], the deepening of the Bering Straits [*Einarsson et al.*, 1967] and/or the Greenland-Scotland ridge [*Wright and Miller*, 1996], and emergence of the Panama Isthmus [*Keigwin*, 1978, 1982; *Keller et al.*, 1989; *Mann and Corrigan*, 1990; *Haug and Tiedemann*, 1998].

Ruddiman and Raymo [1988], *Ruddiman et al.* [1989], and *Ruddiman and Kutzbach* [1991] suggested that the initiation of Northern Hemisphere glaciation was caused

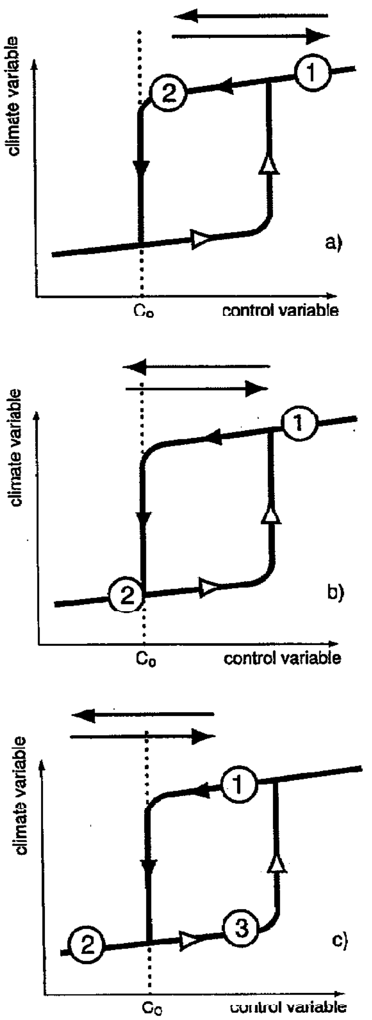

Figure 3. Bifurcation of the global climate system. For example the control variable could be North Atlantic salinity and the climate variable could be production of NADW. a) An insensitive system and the control variable does not vary greatly with large changes in the control variable. b) The control variable drops beneath the critical threshold point C0 (point 2) and thus there is a major change in the climate variable, however by return the control variable to its original state, the system is reversible and the climate variable returns to its original point 1. c) The control variable drops beneath the critical threshold point C0 (point 2), however returning the control variable to its original state does not reverse the change and the climate variable remains at point 3. An additional change to the control variable is required to over come the bifurcation and return the climate variable back to point 1. Hence, if this additional change is not possible within the system, the threshold becomes an irreversible one. It should be notes that returning the system back to its initial boundry contions by going beyond point 3 may take the system back to a new state of equilibrium that is different from the initial state.

by progressive uplift of the Tibetan-Himalayan and Sierran-Coloradan regions. This may have altered the circulation of atmospheric planetary waves such that summer ablation was decreased, allowing snow and ice to build-up in the Northern Hemisphere. There is much speculation as to whether: orography [*Charney and Eliasson*, 1949; *Bolin*, 1950], differential heating of land and sea surfaces [*Sutcliffe*, 1951; *Smagorinsky*, 1953], or a combination of both [*Trenberth*, 1983], control the structure and direction of the planetary waves. However, most of the Himalayan uplift occurred much earlier between 20 Ma and 17 Ma [*Copeland et al.*, 1987; *Molnar and England*, 1990] and the Tibetan Plateau reached its maximum elevation during the late Miocene [*Harrison et al.*, 1992, *Quade et al.*, 1989]. *Raymo et al.* [1988], *Raymo* [1991, 1994b] and *Raymo and Ruddiman* [1992] then suggesting that the uplift caused a massive increase in tectonically driven chemical weathering in the late Cenozoic. They argue that carbonation of rainwater removes CO_2 from the atmosphere and forms a weak carbonic acid solution. Dissociated H^+ ions in the acidified rainwater by hydrolysis leads to enhanced chemical weathering of rocks. Only weathering of silicate minerals makes a difference to atmospheric CO_2 levels, as weathering of carbonate rocks by carbonic acid returns CO_2 to the atmosphere. Bi-products of hydrolysis reactions affecting silicate minerals are biocarbonates (HCO_{3-}) anions and calcium cations. These, when washed into the oceans, are metabolised by marine plankton and are converted to calcium carbonate. The calcite skeletal remains of the marine biota are ultimately deposited as deep-sea sediments and hence lost from the global biogeochemical carbon cycle for the duration of the life cycle of the oceanic crust on which they were deposited. Consequently, atmospheric CO_2 could have been depleted causing a cooling of the global climate and thus the OHNG. This theory, however, suffers from a number of major draw-backs, 1) there is debate whether the Strontium (Sr) isotope data can be used as evidence of continental weathering [*Kirshnaswami et al.*, 1992; *Berner and Rye*, 1992; *Huh and Edmund*, 1998], 2) there seems to be no obvious negative feedback mechanism to prevent a complete depletion of the relatively small reservoir of atmospheric CO_2 [e.g., *Berner*, 1994; *Compton and Mallinson*, 1996, *Raymo*, 1994b] and 3) there is now evidence that suggest that there was no decrease in atmsopheric carbon dioxide during the Miocene [*Pagani et al.*, 1999; *Pearson and Palmer*, 2000].

A second key tectonic control invoked as a trigger for the ONHG is the closure of the Pacific-Caribbean gateway. *Haug and Tiedemann* [1998] suggest it began to emerge at 4.6 Ma and finally closed at 1.8 Ma. However, there is still considerable debate on the exact timing of the closure [*Burton et al.*, 1997; *Vermeij*, 1997; *Frank et al.*, 1999].

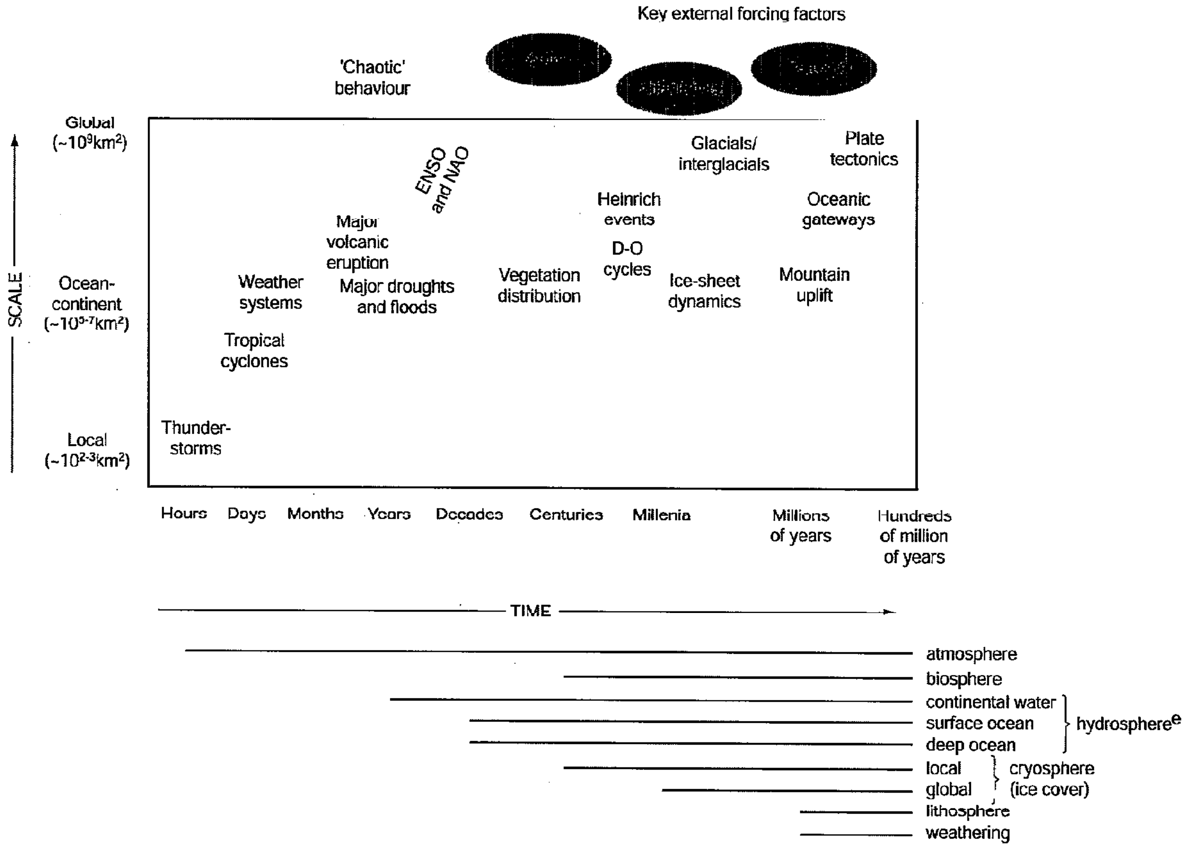

Figure 4. The spatial and temporal dimensions of the Earth's climate system plotted on logarithmic scales. The key forcing functions and response time of different section of the global climate system are also shown. D-O cycles = Dansgaard-Oeschger cycles.

The closure of the Panama gateway however causes a paradox [*Berger and Wefer*, 1996] as there is considerable debate whether it would have helped or hindered the intensification of North Hemisphere glaciation. The reduced inflow of Pacific surface water to the Caribbean would have increased the salinity of the Caribbean. This would have increased the salinity of water carried northward by the Gulf Stream and North Atlantic Current, thus enhancing deepwater formation [*Mikolajewicz et al.*, 1993; *Berger and Wefer*, 1996]. Increased deep-water formation could have worked against the initiation of Northern Hemisphere glaciation as it enhances the oceanic heat transport to the high latitudes and would have opposed ice sheet formation (see Figure 6). This enhanced Gulf Stream would also have pumped more moisture northward, stimulating the formation of ice sheets [*Mikolajewicz et al.*, 1993; *Berger and Wefer*, 1996]. *Driscoll and Haug* [1998] also argue that this increased moisture supply would have enhanced freshwater delivery to the Arctic via Siberian Rivers. This freshwater input to the Arctic would have facilitated sea ice formation (fresher water has higher freezing point), increased albedo and isolated the high heat capacity of the ocean from the atmosphere. So it would have acted as a negative feedback on the efficiency of the "deep water conveyor belt" heat pump [*Broecker*, 1997a].

Tectonic forcing alone cannot explain the fast changes of both the intensity of glacial-interglacial cycles and mean global ice volume. It has, therefore, been suggested that changes in orbital forcing may have been an important mechanism contributing to the gradual global cooling and the subsequent rapid intensification of Northern Hemisphere glaciation [*Lourens and Hilgen*, 1994; *Maslin et al.*, 1995a; 1998a; *Haug and Tiedemann*, 1998]. This theory extends the ideas of *Berger et al.* [1993] by recognizing distinct phases during the Pleistocene and late Pliocene, characterized by the relative predominant strength of the

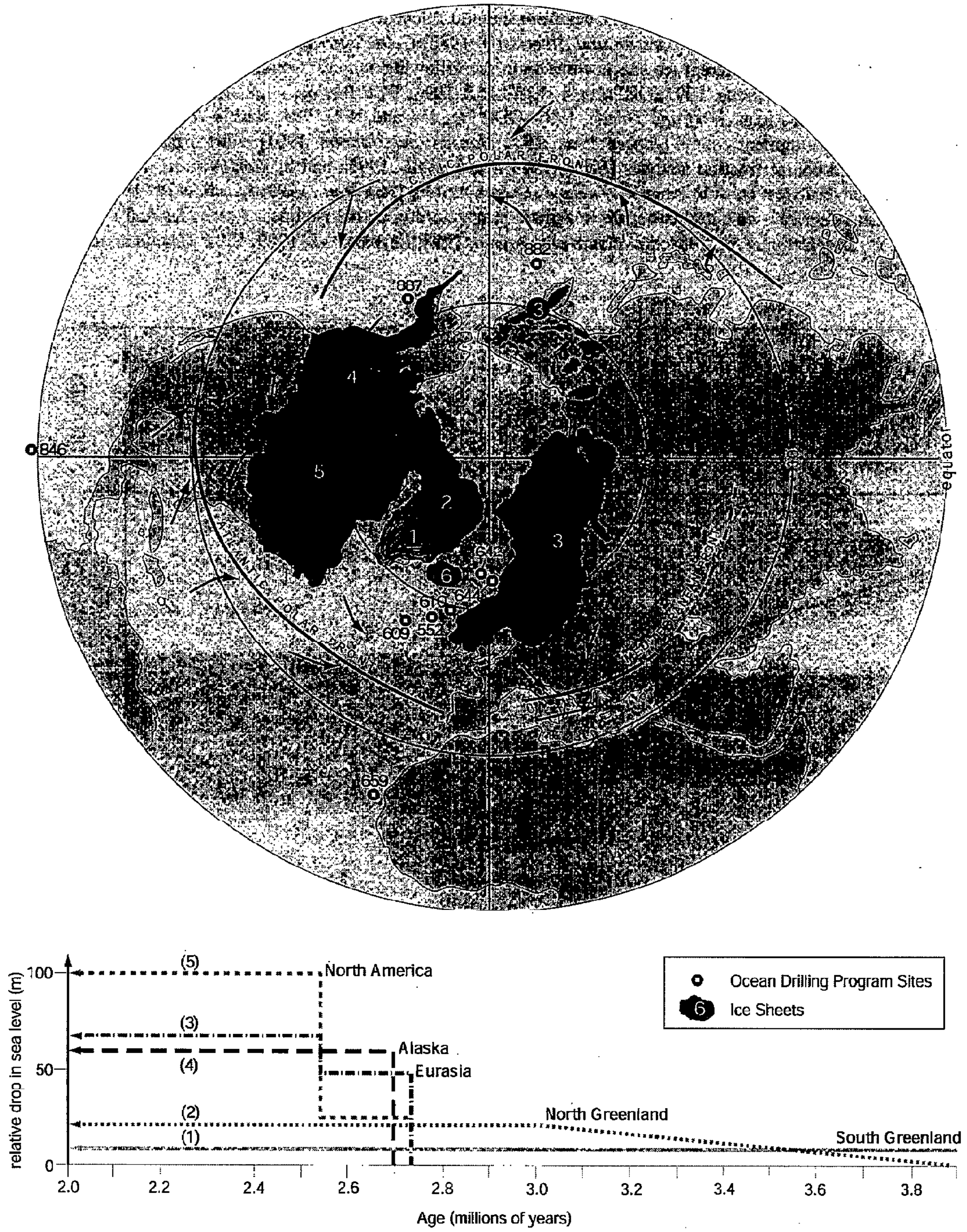

Figure 5. Timing of the intensification of Northern Hemisphere Glaciation [adapted from *Maslin et al.*, 1998a]. Map shows the extent of the Northern Hemisphere ice sheets during the Last Glacial Maximum [*CLIMAP*, 1976, 1981]. The separate ice sheets are identified by different colours. The **modern** climatic fronts are also shown to represent the possible atmospheric circulation of the pre-glacial Pliocene. The graph shows the estimated time at which each ice sheet was large enough to reach the edge of the continents and thus release icebergs, compared with its relative effect on the sea level, estimated from the change in the global $\delta^{18}O$ signal [*Tiedemann et al.*, 1994; *Shackleton et al.*, 1995]. Ice-

land seems to have had repeated glacial episodes from the mid-Pliocene onwards, but no clear dates are yet available for when this became sustained [*Einarsson and Albertsson*, 1988; *Geirsdottir and Eiriksson*, 1994]. The data for the onset of ice rafting of the different ice sheets come from the following sources: Southern Greenland - coarse fraction analysis [e.g., *Wolf and Thiede*, 1991: ODP Leg 151 and 152, 1994; *Wolf-Welling et al.*, 1995], Northern Greenland - coarse fraction analysis [e.g., *Wolf and Thiede*, 1991: ODP Leg 151 and 152, 1994; *Wolf-Welling et al.*, 1995], Eurasian Arctic - lithic fragment counts [*Jansen et al.*, 1990; *Jansen and Sjøholm*, 1991] and Northeast Asia - magnetic susceptibility and coarse fraction analysis [*Haug*, 1995; *Haug et al.*, 1995a and b; *Maslin et al.*, 1995a and 1998a], Alaska and the Northwest coast of America - magnetic susceptibility [*Rea et al.*, 1993; *Maslin et al.*, 1995a and 1998a] and Northeast America - calcium carbonate, magnetic susceptibility, stable isotopes, ostracodes and coarse fraction analysis [e.g., *Shackleton et al.*, 1984; *Ruddiman and Raymo*, 1988; *Raymo et al.*, 1989, 1992; *Cronin et al.*, 1996].

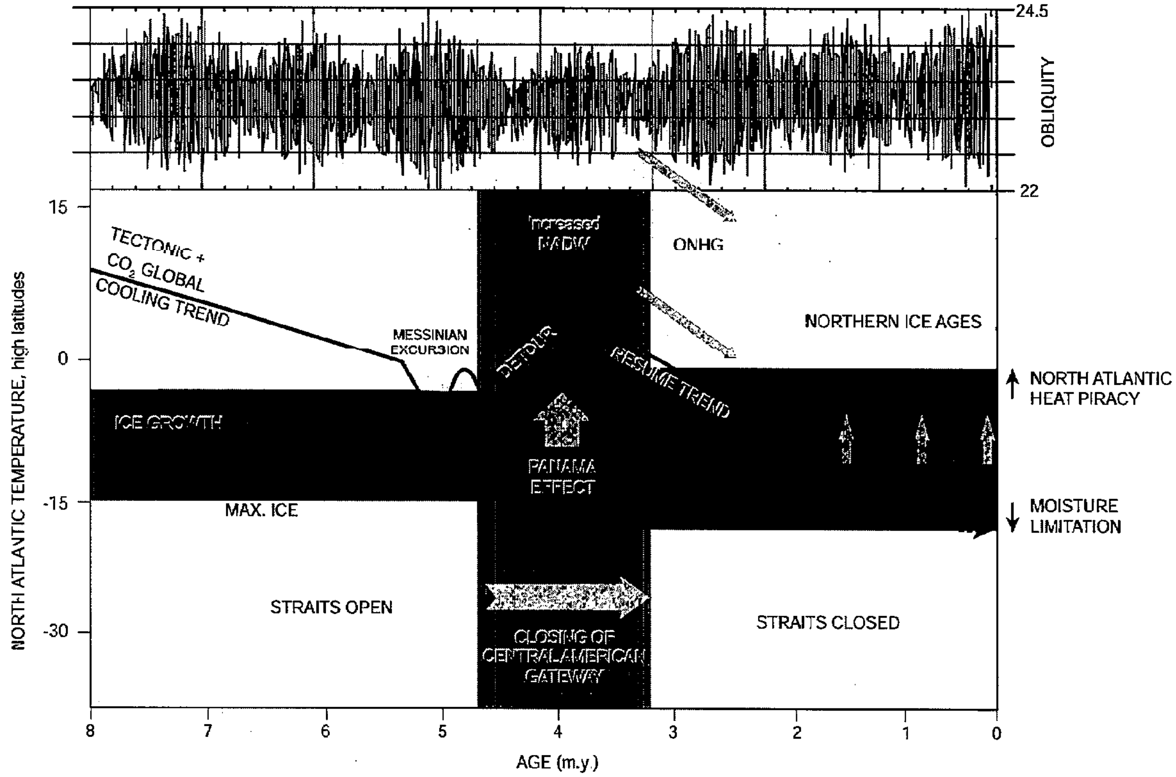

Figure 6. Summary of the causes of the Onset of Northern Hemisphere Glaciation (ONHG). Note the detour of the cooling trend and the expansion of the temperature range of ice growth caused by the closure of the central American gateway. Note also the kick in obliquity which occurs between 3.2 Ma and 2.5 Ma which drives the continued cooling of the climate system and the ONHG [adapted from *Berger and Wefer*, 1996].

different orbital parameters during each interval. *Maslin et al.* [1995a, 1998a] and *Haug and Tiedemann* [1998] have suggested that the observed increase in the amplitude of orbital obliquity cycles, from 3.2 Ma onwards, may have increased the seasonality of the Northern Hemisphere, thus initiating the long-term global cooling trend (see Figure 6). The subsequent sharp rise in the amplitude of precession and consequently in insolation at 60°N between 2.8 Ma and 2.55 Ma may have forced the rapid glaciation of the Northern Hemisphere. This theory is supported by simulation of the Northern Hemisphere ice-sheet volume variation made by *Li et al.* [1998] with the LLN 2-D model [*Galleé et al.*, 1991, 1992]. In these experiments, ice volume fluctuations were forced by insolation variations

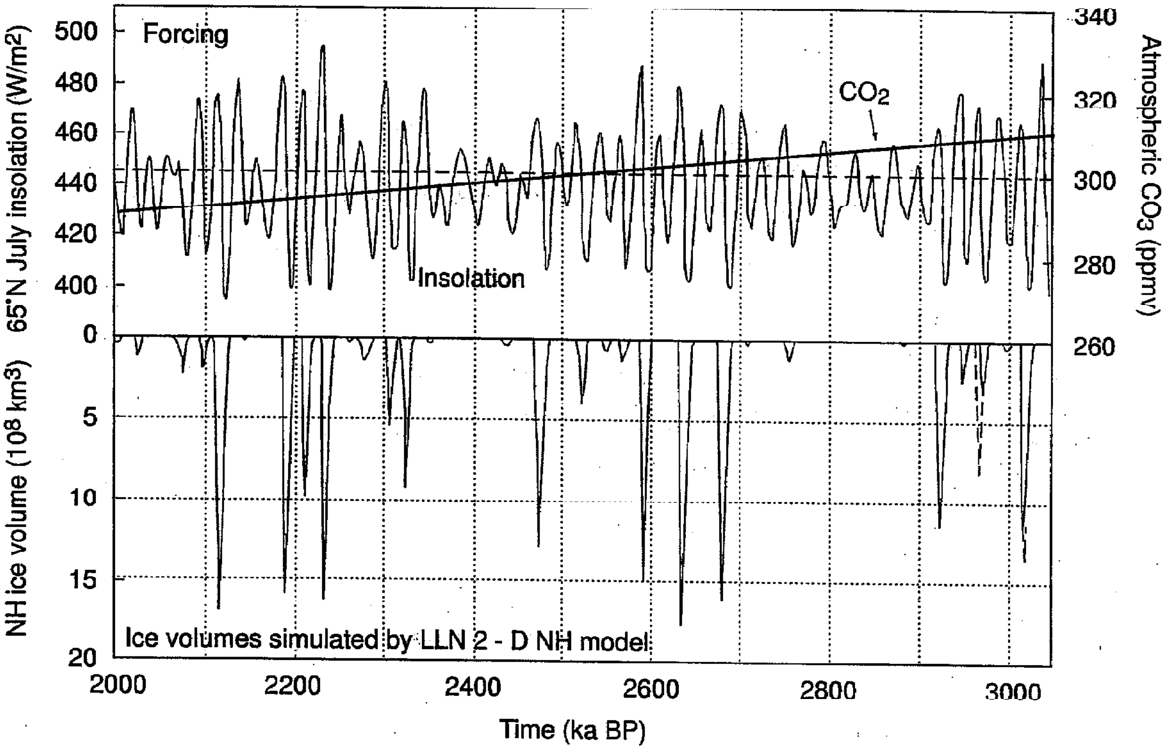

Figure 7. *Li et al.* [1998] and *Maslin et al.* [1998a] clearly showed from modelling results that Northern Hemisphere ice sheets could build-up around 2.5 Ma by only the variations in the orbital parameters. The model, however, due to the lack of climatic feedbacks fails to sustain the ice sheets after the initial forcing has been removed. The July 65°N insolation variation [*Loutre and Berger*, 1993] (solid line, upper panel), the tectonically-induced linear CO_2 concentrations [*Saltzman et al.*, 1993] (dashed line, upper panel), and the simulated Northern Hemisphere ice sheet volume with the LLN 2-D model (solid line, lower panel), from 3.05 Ma to 2 Ma BP [*Li et al.*, 1998] are shown.

[*Loutre and Berger*, 1993] with the assumption of a linearly decreasing atmospheric CO_2 concentration [*Saltzman et al.*, 1993]. Three major periods of glaciation between 2 Ma and 3 Ma were simulated, each one corresponding to the periods of large amplitude in the insolation signal and match with the three key steps in the intensification of Northern Hemisphere Glaciation (Figure 7).

I.c. Synthesis.

We still do not know what caused the Northern Hemisphere to glaciate some two and half million years ago. A plausible theory could be that the Tibetan uplift caused long term cooling during the late Cenozoic. The closure of the Panama Isthmus then may have delayed the onset of Northern Hemisphere Glaciation but ultimately provide the moisture which allowed intensive glaciation to develop at warmer high latitude temperatures (see Figure 6). The global climate system seems to have reached a threshold at about 3 Ma, when orbital configuration may have pushed global climate across this threshold, building all the major Northern Hemisphere ice sheets in a little over 200 kyrs.

II. GLACIAL-INTERGLACIAL CYCLES

II.a. Feedback Mechanisms: the Conventional View.

Glacial-Interglacial cycles are forced by changes in the Earth's orbital parameters. These cycles are, however, not caused by Earth's orbital parameters but rather the Earth's climate system feedback mechanisms. An illustration of this is that the insolation received at the critical 65°N was the same 18,000 during the LGM as it is today [*Berger and Loutre*, 1991; *Laskar*, 1990]. This section will not discuss the orbital parameters and their various influences as that has been done many times in great detail [e.g., *Milankovitch*, 1949; *Hays et al.*, 1976; 1984; *Ruddiman and McIntyre*, 1981; *Imbrie et al.*, 1992; 1993; *Berger and Loutre*, 1991; *Laskar*, 1990, see *Wilson et al.*, 2000 for clear review of the different orbital parameters and Appendix I). However, to illustrate the interaction of the global climate system feedback mechanisms these are discussed first in the context of glacial-interglacial and then rapid climate transitions. We present the discussion of the general consensus about the feedback mechanisms, followed by discussion of the alternatives. The insolation changes received by the Northern Hemisphere temperate zone is thought to be critical for glacial-interglacial cycles, because the Southern Hemisphere is presumably unable to drive glacial-interglacial as the expansion of the ice sheets is limited by the Southern Ocean. The critical factor is total summer insolation, as ice sheets surplus must survive the summer melting. So both the glaciation and deglaciation feedback mechanisms start with changes in summer 65°N insolation (Figure 8). The conventional view is that as ice starts to build-up on the northern continents it produces it own sustainable environment primarily by increasing the albedo [e.g., *Hewitt and Mitchell*, 1997]. The next critical stage is when the ice sheets, particularly the Laurentide become big enough to deflect the atmospheric planetary waves [*COHMAP*, 1988]. This changes the storm path across the North Atlantic Ocean and prevents the Gulf Stream penetration as far north as today. This surface ocean change and the increased melt-water in the Nordic Seas and Atlantic Ocean ultimately reduces the production of deep water [e.g., *Broecker*, 1991]. This in turn reduces the amount of warm water pulled northwards. All of which leads of increased cooling in the Northern Hemisphere and expansion of the ice sheets.

There are then secondary feedback mechanisms which also help drive the system towards the maximum possible glacial conditions. These include changes in the carbon cycle which reduces both atmospheric carbon dioxide and methane [e.g., *Chapellaz et al.*, 1993; 1997; *Brook et al.*, 1996]. Sigman and *Boyle* [2000] provide an excellent review of all the main controls on the carbon cycle and the possible causes of reduced glacial atmospheric carbon dioxide. They speculate that glacial-interglacial changes in atmospheric carbon dioxide may be primarily driven by changes in oceanography in the Southern Ocean. This could have altered the nutrient supply to the surface waters, hence surface water productivity. Increased glacial surface water productivity would have down-drawn atmospheric carbon dioxide into the surface water to produce organic matter through photosynthesis. However, the controls on the glacial-interglacial carbon cycle are still very poorly understood. Glacial periods by their very nature have drier conditions which reduces atmospheric water vapor. For example Lea et al. [2000] provides clear evidence that the water vapor production of the equatorial Pacific zone was greatly curtailed during the last five glacial periods. All three, CO_2, CH_4 and water vapor are crucial greenhouse gases and any reduction in them leads to general global cooling (Figure 8), which in turn furthers glaciation.

These feedbacks are prevented from becoming a run away affect by 'moisture limitation'. As the warm surface water is forced further and further south, supply of the moisture that is required to build ice sheets decreases. Moreover it is very clear that ice sheets are naturally unstable [*Dowdeswell et al.*, 1999] and these feedbacks are constantly altering direction during the whole glacial period, hence it takes 80 ka to achieve the maximum ice extent during the LGM and that period is characterized by rapid oscillation such as the Heinrich events and the D-O cycles.

The natural instability of ice sheets means that deglaciation is much quicker than glaciation. In the case of Termination I it lasts a maximum of 4 ka including the Younger Dryas period. The increase in summer 65°N insolation [e.g., *Imbrie et al.*, 1993] leads to the initial melting of the Northern ice sheets. This raises sea level that then undercuts the ice sheets adjacent to the oceans, which in turns raises sea level. This sea level feedback mechanism is extremely rapid [*Fairbanks*, 1989]. Once the ice sheets are in retreat then the other feedback mechanisms discussed for glaciation are thrown into reverse (see Figure 9) including a massive increase in the greenhouse gases CO_2, CH_4 and water vapor. These feedbacks are prevented from becoming a run away affect by the limit of how much heat the North Atlantic can steal from the South Atlantic to maintain the interglacial deep water overturning rate.

IIb. Feedback Mechanisms: Possible New View?

The latest twist concerning orbital forcing and the feedback mechanisms has been shown by *Shackleton* [2000]. *Shackleton* [2000] suggests from a detailed tuning of the Antarctic Vostok ice core and deep ocean records that at the 100,000 year period, atmospheric carbon dioxide, Vostok air temperatures and deep water temperatures are in phase with orbital eccentricity; whereas ice volume lags these other variables. This suggests that orbitally induced changes in the carbon cycle and hence atmospheric carbon dioxide is the primary feedback causing the 100 ka glacial-interglacial cycles and not the conventional ice sheet dominated view. So in the proposed glaciation feedbacks carbon dioxide could be the primary means of transferring the orbital forcing into the global climate system. It also suggests that Northern Hemisphere ice sheet size is not the

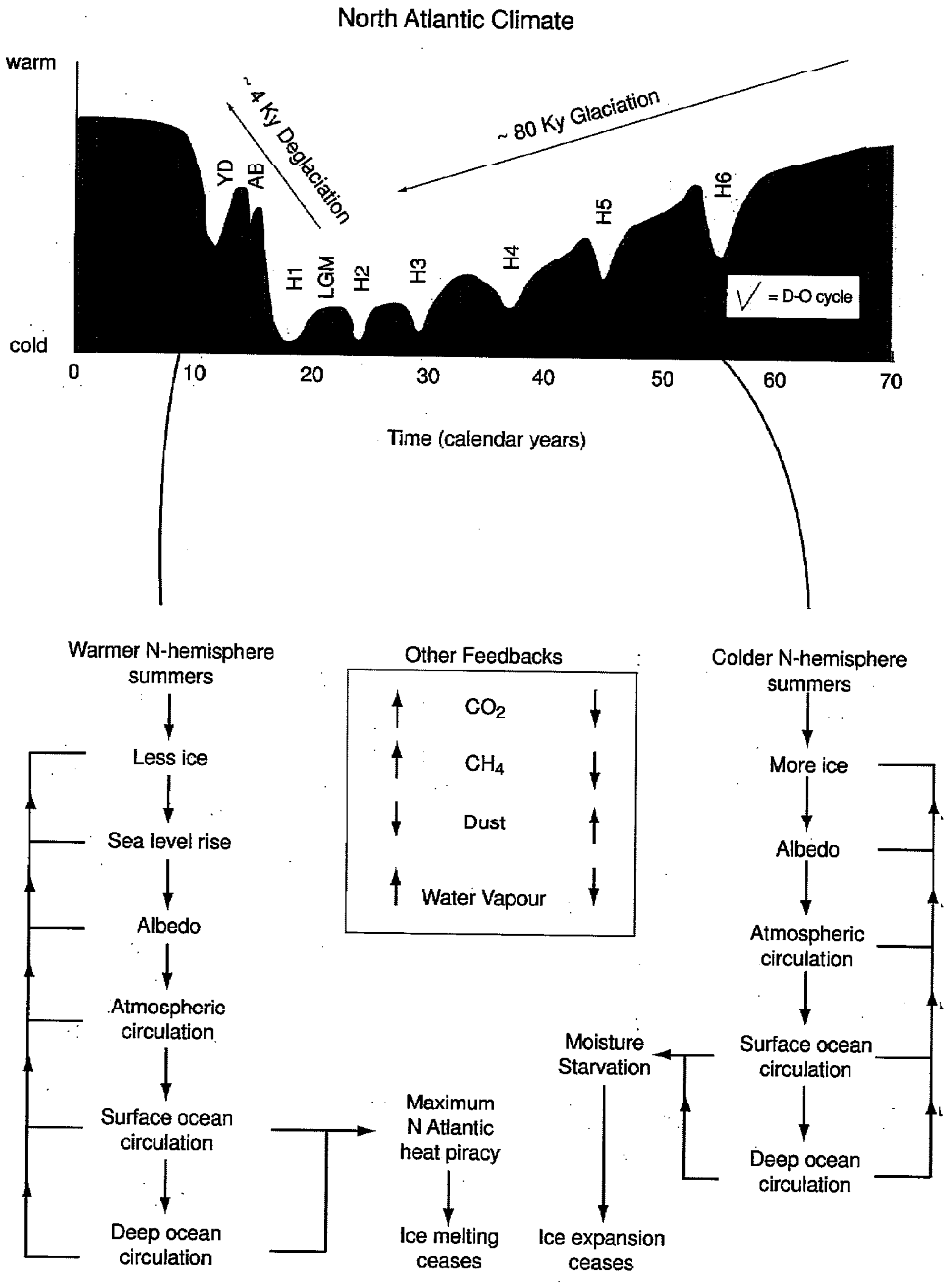

Figure 8. Detailed break down of the Mid-Pleistocene Revolution by *Mudelsee and Stattegger* [1997] demonstrating that there is a delay of 200 ka between the significant increase in global ice volume and the start of the 100 ka glacial-interglacial cycles.

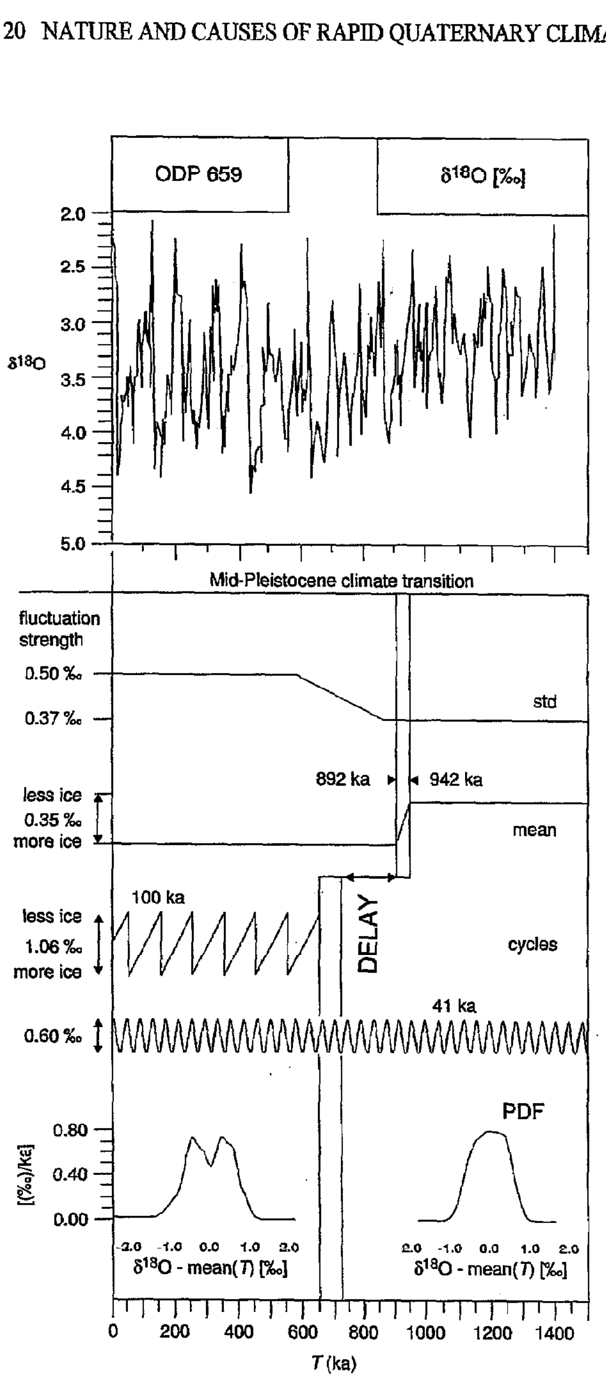

Figure 9. Summary of the conventional view of the feedback mechanism forced by insolation at 65°N which drive glaciation and deglaciation. H = Heinrich events, LGM = Last Glacial Maximum, AB = Allerød Bølling Interstadial, YD = Younger Dryas and D-O = Dansgaard-Oeschger cycles.

initial control on deep water circulation and hence temperatures. However, it must be remember that this new interpretation is reliant on the robustness of the age models from both deep sea sediments and ice cores [Shackleton, 2000]. When dealing with multiple glacial-interglacial cycles there are no radiometric dating techniques available and hence tuning the age models to orbital parameters is the only method available and this can be highly subjective. In addition, others have argued that the 100 ka cycle that is observed in the spectral records is not eccentricity but rather deglaciation triggered every 4th or 5th precessional cycle. Hence the correlation between eccentricity and the paleoclimate proxies found by *Shackleton* [2000] may be coincident. Moreover no causal link has been suggested between orbital eccentricity and changes in the global carbon cycle. There is evidence, however, that ocean productivity and hence atmospheric carbon dioxide is influenced by orbital precession [e.g., *Cane*, *1998*; *Beaufort et al.*, 1999] which is in turn modulated by orbital eccentricity.

The possible in-phase relationship between Vostok air temperatures and deep water temperature is easier to explain as recent evidence indicates that the Southern Ocean has a much more important role to play in the control of the glacial-interglacial cycles than previously thought [*Keeling and Stephen*, 2001]. *Seidov et al.* [2001; this volume] and *Keeling and Stephens* [2001] provide a possible mechanism linking Antarctic air temperatures and deep water formation. They have demonstrated the sensitivity of the whole global deep water system to the presence or absence of melt-water in the Southern Ocean. Hence Antarctic air temperatures govern whether the Antarctic ice sheet is expanding, static or retreating. This in turn will control the amount of melt-water in the Southern Ocean and thus the temperature of the deep waters. Variations in the amount and temperature of deep water has a direct effect on global climate. From the physical point of view, the deep ocean is the only candidate for driving and sustaining internal long-term climate change (of hundreds to thousands years) because of its volume, heat capacity, and inertia. Long-term climate change is, therefore, largely regulated by the processes of oceanic heat transfer [e.g., *Broecker* 1995, *Keigwin et al.*, 1994, *Shaffer and Bendtsen*, 1994; *Jones et al.*, 1996; *Rahmstorf et al.*, 1996; *Seidov and Maslin*, 1999]. An additional interesting link is that *Lea et al.* [2000] found that equatorial Pacific sea surface temperature and salinity was in-phase with Antarctic air temperatures and hence leds ice volume changes by about 3,000 years.

So we can speculate that changes in the global carbon cycle, Antarctic air temperatures and equatorial climate could independently respond to orbital forcing. Alternatively one or several of these variables controls the others, for example changes of atmospheric carbon dioxide could control equatorial and Antarctic temperatures. The climate changes over Antarctic then in turn could influence the deep water system which then could influence the pull of the Gulf Stream northward to the formation sites of the North Atlantic Deep Water (NADW). These changes along with the local critical changes in the 65°N insolation instigate either build or collapse of the Northern Hemisphere ice sheets.

II.c. Synthesis

The thought provoking paper by *Shackleton* [2000] forces us to re-assess the conventional view of what causes glacial-interglacial cycles. It provides a major challenge, does Northern Hemisphere ice volume or the global carbon cycle primarily control glacial-interglacial cycles and what is the involvement of orbital forcing? However, before we throw out the conventional view, which has stood the test of time, and embrace a new view there are a large number of problems that need to be addressed. We suggest the primary one is whether a 100 ka cycle represents orbital eccentricity or rather deglaciations triggered by everyother 4th or 5th precessional cycle. This is, thus, an exciting time for paleoclimatology when even the basic view of what causes glacial-interglacial cycles may be wrong.

III. THE MID-PLEISTOCENE REVOLUTION

III.a. A Switch to Non-linear Global Climate System?

The Mid-Pleistocene Revolution (MPR) is the term used to denote a marked prolongation and intensification of the global glacial-interglacial climate cycles which occurred between 900 and 650 Ka [*Berger and Jansen*, 1994]. Prior to the MPR, since at least the onset of Northern Hemisphere glaciation (~2.75 Ma), the global climate conditions appear to have responded linearly to the obliquity (41 ka) orbital periodicity [*Imbrie et al.*, 1992], i.e., the glacial-interglacial cycles occur with a frequency of 41 ka. After about 800 ka glacial-interglacial cycles become more pronounced and occur with a frequency of approximately 100 ka. Hence MPR marks a switch in the timing of glacial-interglacial cycles from 41 ka to 100 ka [*Berger and Jansen*, 1994]. *Imbrie et al.* [1993] call this the "100 ka problem", as only the last 8 glacial-interglacial cycles have occurred with this frequency and increased intensity. The cyclicity and amplitude of the orbital parameters which force long term global climate change, e.g., eccentricity (~100 ka), obliquity (~41 ka) and precession (~21/19 ka), do not vary during the MPR [*Berger and Loutre*, 1991]. This suggests the MPR is an internal re-organization of the feedback mechanisms that translate orbital forcing into global climate change. Moreover, the 100 ka eccentricity signal is by far the weakest of the orbital parameters and has been thought too be phase-lagged to force directly a 100 ka global climate cyclicity. The MPR, thus could be a change from a linearly-forced climate system to the non-linearly forced climate system which we have at present [*Imbrie et al.*, 1993]. This is, however, assuming that the 100 ka cyclicity that is observed for the last 8 glacial-interglacial cycles reflects an eccentricity signal. It has been argued that the spectral peak of 100 ka is not associated with eccentricity which has two spectral peaks near 100 ka and one at 413 ka; rather the spectrum is caused by deglaciations being triggered by every fourth or fifth precessional cycle [*Raymo*, 1997; *Ridgwell et al.*, 1999]. Hence, the MPR could be an internal adjustment from a obliquity dominated system to a precession dominated system.

During the MPR not only does timing of glacial-interglacial cycles increase but there is also an amplitude increase of the variations of global ice volume. The main causes for this ice volume increase are prolonged glacial periods, evidence of which is provided by high resolution oxygen isotope data from deep sea cores [*Pisias and Moore*, 1981; *Prell*, 1982; *Shackleton et al.*, 1988; *Tiedemann et al.*, 1994; *Berger and Jansen*, 1994; *Raymo et al.*, 1997; *Mudelsee and Stattegger*, 1997]. The MPR, therefore, marks a dramatic sharpening of the contrast between warm and cold periods. *Mudelsee and Stattegger* [1997] used advanced methods of time-series analysis to review the deep sea evidence spanning the MPR and summarized the salient features (Figure 9). The first transition occurs between 942 and 892 ka when there is a significant increase in global ice volume, however, the 41 ka climate forcing continues. This situation persists until about 650-725 ka when the climate system finds a two modal solution and the strong 100 ka climate cycles begin [*Mudelsee and Stattegger*, 1997]. A number of causes have been suggested for the MPR and the subsequent 100 ka 'non-linear' world; these are all based on a threshold model (Figure 1d) and include:

a) Critical size of the Northern Hemisphere ice sheets. *Imbrie et al.* [1993] suggested that the North Hemisphere ice sheets may have reached a critical size during the MPR allowing them to respond non-linearly to eccentricity.

b) Global cooling trend. It has been suggested that long term cooling through the Cenozoic instigated a threshold which allowed the ice sheets to become large enough to ignore the 41 ka orbital forcing and to survive between 80 and 100 ka [*Abe-Ouchi*, 1996; *Raymo et al.*, 1997] *c) Erosion of regolith beneath the Laurentide ice sheet. Clark and Pollard* [1998] suggested that the constant erosion of regolith beneath the Laurentide ice sheet would eventually provide more bedrock for the ice sheet to rest on and hence it would be more stable allowing it to survive longer than the 41 ka driving force.

d) Orbital inclination. A fourth possible orbital parameter has been identified, orbital inclination, which is the 100 ka variation in the angle of the Earth's plane of orbit compared to the average orbit of the solar system [*Muller and MacDonald*, 1997; *Farley and Paterson*, 1995]. It has been argued that this might have changed the total amount of radiation received and could cause the Earth to pass through increased amounts of dust from outer space (Interplanetary Dust Particles, IDPs) which would encourage glacial-interglacial alternations on 100 ka periodicity. It now appears, however, that this process is not likely to have been of influence on ice ages on Earth [*Kortenkamp and McDermott*, 1998]. Moreover, the possibility that the 100 ka cycle is caused by deglaciation every 4th or 5th precessional cycle removes the need for a 100 ka forcing mechanism.

e) Greenland-Scotland submarine ridge. Denton [2000] has envisioned a MPR mechanism based on the uplift of the Greenland-Scotland submarine ridge ca. 950 ka BP (caused by burst of tectonic activity along the Iceland mantle plume) which led to a southward shift of the area of deep-water production from the Arctic to the Nordic seas. This would have had a number of effects on oceanic circulation, especially during times of expanded ice sheets, so that once ice-sheet expansion had commenced, it became much more difficult for the salinity conveyor to re-set into an interglacial mode. In other words, after 950 ka, it became easier for ocean circulation to lock into glacial than interglacial mode, and only occasional highs in the amplitude of the eccentricity-driven precession signal lead to short warm events.

f) Carbon cycle and Atmospheric CO_2. It has been suggested that the reduction of atmospheric CO_2 may have brought the global climate to a threshold allowing it to respond non-linearly to orbital forcing [*Mudelsee and Stattegger*, 1997; *Raymo et al.*, 1997; *Berger et al.*, 1999]. It is also important to consider the latest results of *Shackleton* [2000]. He suggests that the 100 ka eccentricity, atmospheric carbon dioxide, Vostok (Antarctica) air temperatures and deep water temperatures are in phase; whereas ice volume lags these other variables. This is an important finding, if confirmed, as it suggests that atmospheric carbon dioxide and not Northern Hemisphere ice volume may be the primary driving force of the 100 ka glacial-interglacial cycles. The MPR could, thus, have been caused by changes in the internal response of the global carbon cycle to orbital forcing. *Sigman and Boyle* [2000] suggest the Southern Ocean as one of the most important regions modulating atmospheric carbon dioxide. So *Shackleton* [2000] opens the possibility that the Southern Ocean may have become more sensitive to orbital forcing and hence modulated the global carbon cycle. However, what caused this increased sensitivity and whether carbon dioxide changes alone could maintain extended glacial periods is still unknown. The links between Antarctic air temperatures, the Southern Ocean and deep water temperatures is discussed in more details in Sections II IVc.

III.b. Synthesis

At the moment there is no consensus on how and why the MPR occurred. The only real agreement is that it involved a significant internal reorganization of the climate system. The MPR could have been a shift to climate system with a non-linear response to orbital eccentricity [*Imbrie et al.*, 1993] or it may have been a shift from an obliquity to a precession dominated system. *Shackleton* [2000] work provides new ideas for the causation of the MPR including changes in the sensitivity of the global carbon cycle and/or the Southern Ocean to orbital forcing. These ideas have yet to be fully investigated.

IV. RAPID CLIMATE CHANGES IN GLACIAL PERIODS

IV.a. Heinrich Events and Dansgaard-Oeschger Cycles.

Heinrich events are intense and quasi-periodic ice rafting pulses which are thought to originate primarily from the Laurentide ice sheet [e.g., *Ruddiman*, 1977; *Heinrich*, 1988; *Broecker et al.*, 1992; *Bond et al.*, 1992; *Francois and Bacon*, 1993; *Grousset et al.*, 1993; 2000; *Andrews et al.*, 1994; *Gwiazda et al.*, 1996 a and b, *Ramussen et al.*, 1997; *Andrews*, 1998; *Clark et al.*, 1999]. These events occurred against the general background of unstable glacial climate, and represent the brief expression of the most extreme glacial conditions around the North Atlantic. The Heinrich events are evident in the Greenland ice cores as a further 3-6°C drop in temperature from the already cold glacial climate [*Bond et al.*, 1993; *Dansgaard et al.*, 1993]. The Heinrich events have been found to have a global impact [*Clark et al.*, 1999] with evidence for coeval climate changes described from as far field as: South America [*Lowell et al.*, 1995], North Pacific [*Kotilainen and Shackleton*, 1995], Santa Barbara Basin [*Behl and Kennett*, 1996], Arabian Sea [*Schulz et al.*, 1998], China [*Porter and An*, 1995] and the South China Sea [*Wang et al.*, 1999]. Around the North Atlantic much colder conditions are found [*Grimm et al.*, 1993; *Thouveny et al.*, 1994] see

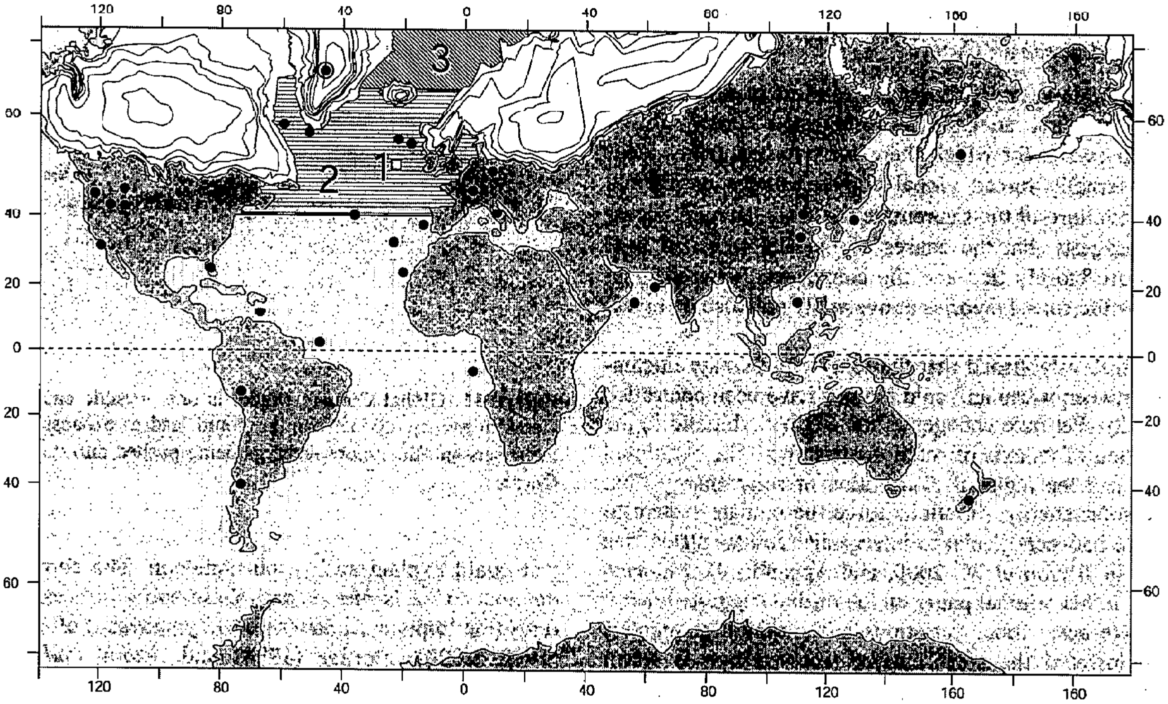

Figure 10. Map showing sites where paleo-records have linked the local climate and environmental changes to the Heinrich events. Number 1 is the location of the original *Heinrich* [1988] study. Number 2 is the North Atlantic which has been covered extensively by a number of studies [e.g., *Bond et al.*, 1992; 1993; Sarnthein et al., in press] and Number 3 is an extensive studied Nordic Seas that has demonstrated that the Greenland and Fenno-Scandinavian ice sheet seems to surge at different times to the Heinrich events [e.g., *Sarnthein et al.*, 1995; *McCabe and Clark*, 1998; *Dowdeswell et al.*, 1999].

Figure 10) and in the North Atlantic Ocean huge armadas of melting icebergs reduce sea surface temperatures by another 1-2°C and reduce the surface salinity by up to 4‰ [*Maslin et al.*, 1995b; *Cortijo et al.*, 1997; *Chapman and Maslin*, 1999; *Vidal et al.*, 1999].

Detailed studies of the sequence of events in ocean sediments and ice cores showed that Heinrich events occurred on an average of 7200 ± 2400 calendar years [Sarnthein et al., in press) in the time interval between about 70 and 10.5 ka. In between the Heinrich events there are much higher frequency, but smaller amplitude events occurring at about every 1500 years, which are referred to as Dansgaard-Oescheger events or cycles [*Dansgaard et al.*, 1993; *Bond et al.*, 1997].

Dansgaard-Oeschger (D-O) cycles were first identified in the Greenland ice core records [*Dansgaard et al.*, 1993]. A succession of short lived 'warm' events or Greenland interstadials (GIS) characterize the ice core records of the last glacial episode and are numbered down from the 'Bolling' as GIS 1 to GIS 24 at 105 ka. The D-O stadials or cold sections of the D-O cycle have been found in the ice rafting records of the North Atlantic [e.g., *Bond and Lotti*, 1995]. These stadials are characterized by increase meltwater and ice rafted debris originating from Iceland and East Greenland [*Bond and Lotti*, 1995; *Sarnthein et al.*, in press]. These 1500-year cycles seem to persist into the Holocene interglacial [*Bond et al.*, 1997; 1999; *Campbell et al.*, 1998; see below] as well as during earlier glacial and interglacial stages [*Oppo et al.*, 1998; *Hodge*, 2000]. A precise time scale for the duration and sequence these millennial-scale climate events is uncertain, though the events themselves do not appear to have lasted longer than a few centuries [e.g., *Dowdeswell et al.*, 1995; *Zahn et al.*, 1997; *Sarnthein et al.*, in press; van *Kreveld et al.*, 2000; *Grousset et al.*, 2000, in press; *Scourse et al.*, 2000]. Furthermore, the transitions marking the beginnings and ends of each Heinrich and D-O event are particularly rapid, probably lasting no more than a few decades, indicating that climate responded in a step-like series of jumps to whatever driving mechanism initiated them.

IV.b. Possible Causes of the Heinrich Events and Dansgaard-Oeschger Cycles.

To examine the possible causes of these millenial-scale events, we first analysis the suggested causes of the Heinrich events for which there are two competing theories: externally forced global climate change or internal periodic failure of the Laurentide ice sheet. Second, recent work suggests that the causes of the Heinrich and D-O events are closely tied and the connection between them and how the causal theories above apply will also be investigated.

It is well established that the long-term climate fluctuations between warm and cold periods have been controlled externally. Periodic changes in the Earth's orbit and in the inclination of its axis of rotation affect both the net global receipt and the regional distribution of solar energy flux. These solar energy variations force the climate system to alternate between glacial to interglacial climate states [see review in *Wilson et al.*, 2000, and Appendix I). *Heinrich* [1988], in his original paper on ice rafting suggested that it may have been minor variations in the orbital parameters which lowered the solar energy received by the North American ice sheet. Furthermore it has been shown that there are harmonics of the orbital variations which could corresponding to the timing of the Heinrich events [Broecker, 1994; Hagleberg et al., 1994]. These variations could have lowered the heat input or increased the moisture supply to the Laurentide ice sheet causing it to expand, pushing more ice out into the ocean (see Figure11). The global climate model was first put forward by *Broecker* [1994] in response to the work of *Lowell et al.* [1995] who showed that the glaciers of the Chilean Andes in South America expanded at the same time as the Heinrich events. This evidence was interpreted as indicating that ice masses in both the northern and southern hemispheres expanded and contracted synchronously, which in turn would imply the imposition of some over-riding global forcing mechanism. However, the detailed sequence of events has been shown to be much more complex than this. First, *Bond* [1995] has argued that, for the North Atlantic at least, each Heinrich event is immediately preceded by a short episode of climate cooling, so that climate change actually preceded ice-sheet response. This interpretation was based on planktonic formainifera $\delta^{18}O$ records so could also indicate a increase in salinity of the surface waters. Moreover, *Grousset et al.* [2000] see no evidence of the pre-event cooling. Second, there is growing evidence to suggest that ice-mass changes in the two hemispheres during the last glacial cycle were significantly out of phase [e.g., *Blunier et al.*, 1998], which has led to a number of theories about the possible driving mechanisms that could explain such a phenomenon. The current predominant idea is one of anti-phase shifts in oceanic currents (the 'bipolar climate seesaw hypothesis') of *Broecker* [1998, 2000], *Stocker* [1998] and *Seidov and Maslin* [2000], see Section IVc below.

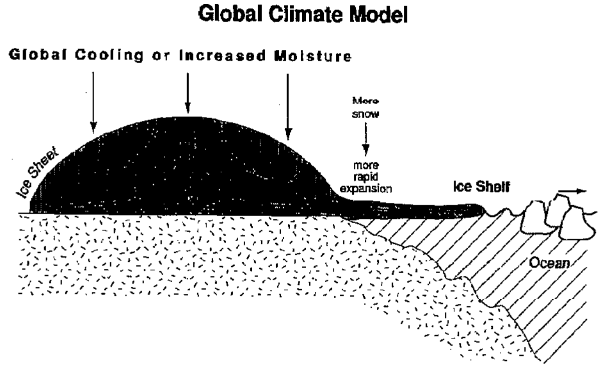

Figure 11. Global Climate Model is one possible cause of the Heinrich events. Global cooling could lead to expansion of the ice sheets and thus more icebergs being pushed into the Atlantic Ocean.

A second theory has been put forward by *MacAyeal* [1993a,b] suggesting that the surges were caused by internal instabilities of the Laurentide ice sheet. This ice sheet rested on a bed of soft unconsolidated sediment, when it is frozen it does not deform, and behaves like cement, and so would have been able to support the weight of the growing ice sheet. As the ice sheet expanded the geothermal heat from within the Earth's crust together with heat released from friction of ice moving over ice, was trapped by the insulating effect of the overlying ice. This 'duvet' effect allowed the temperature of the sediment to increase until a critical point when it thawed. When this occurred the sediment became soft, and thus lubricated the base of the ice sheet causing a massive outflow of ice through the Hudson Strait into the North Atlantic (see Figure 12). This, in turn, would lead to sudden loss of ice mass, which would reduce the insulating effect and lead to re-freezing of the basal ice and sediment bed, at which point the ice would revert to a slower build-up and outward movement. According to *MacAyeal* [1993a, b] this system of progressive ice build-up, melting and surge, followed by renewed build up has an approximate periodicity of 7,000 years, which compares with the interval between the last six Heinrich events which have been calculated by *Sarnthein et al.* [in press] to be an average of 7200 ± 2400 calendar years.

The *MacAyeal* [1993] ice surge hypothesis as this seems to explain many of the details of Heinrich events, espe-

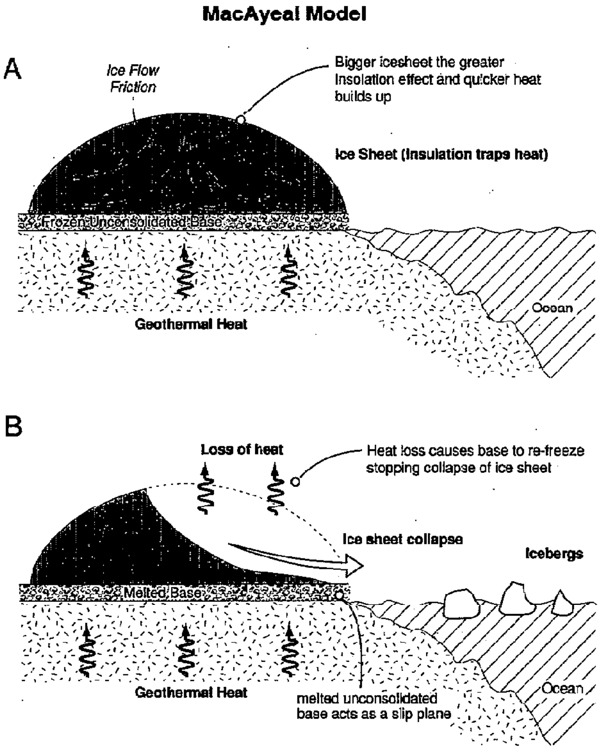

Figure 12. MacAyeal or free oscillating ice sheet collapse model is one possible cause of the Heinrich events. It is suggested that geothermal and fractional heat builds up at the base of the ice sheet and causes it to melt triggering the ice sheet collapse.

cially the rapid onset of these events which is evident in sediments records [*Dowdeswell et al.*, 1995]. X-ray photographs of some deep sea cores show that the uppermost tier of fossil burrows are preserved in the sediment deposited immediately preceding the Heinrich events [*McCave*, 1995]. This implies that the ice-rafted debris must have been deposited almost instantly, i.e., within a few years, since it is usual for these fossil burrows to be obliterated by the action of subsequent ocean floor animals. The Heinrich events, therefore, began with a huge and rapid input of sediment which is consistent with an ice sheet surge. The idea of self-destabilizing ice has a further advantage over the 'Global climate model' since the response time of large 3 km thick ice sheets to external forcing likely to be very slow (on the order of thousands of years) which does not fit well with the evidence of the shear rapidity of these events.

Heinrich events, however, can not be considered in isolation as they are part of the general instability that characterizes glacial periods. Hence, the third possible cause of the Heinrich events which has been suggested is the destabilization of the Laurentide ice sheets triggered by sea level changes induced by the 1,500 year D-O cycles. *Sarnthein et al.* [in press] and *van Kreveld* [2000] present evidence that suggest that ice surges from Iceland and East Greenland could have produced significant increases in sea level, possibly big enough to start under cutting the Laurentide icesheet and thus precipitating a full Heinrich event. Support for this theory comes from the detailed analysis of the sources of ice rafted material in the Heinrich layers. From the detailed break down of H1, H2, H4 and H5 it has been shown that European ice rafted debris was deposited in the North Atlantic upto 1,500 years before the Laurentide material [*Grousset et al.*, 2000, in press; *Scourse et al.*, 2000]. Referring back to the climate change scenarios suggested at the beginning of this paper, it is possible that a critical sea level threshold is exceeded once in every three Dansgaard-Oeschger cycles, precipitating the collapse of the Laurentide ice sheet. This raises a further issue of what causes the Dansgaard-Oeschger cycles?

Again the arguments for causation fall in to the two camps; internal vs external focring. There are two possible internal explainations. This first is a simple MacAyeal type binge-purge process controlling the East Greenland icesheet with a periodicity if 1,500 years [*Sarnthein et al.*, in press; *van Kreveld et al.*, 2000]. Successive failures of the Greenland ice sheet would have a small effect on sea level to the critical point when it influenced the Laurentide ice sheet [*Sarnthein et al.*, in press; *van Kreveld et al.*, 2000]. The second possible internal mecahnism could be an internal oscillation of the deep water system driven by alternating sea ice extent in the Southern Ocean and ice sheet surges in the North Atlantic. This idea and the bipolar seesaw are discussed at length in Section IVd. However, *Scource et al.* [2000] argue for an external climate forcing as suggested by *Broecker* [1994] and Hagleberg et al. [1994]. They have excellent deep-sea core evidence that the British ice sheet surged both before and at the same time as Heinrich event 2. The precursor event occurred 700 to 1000 years before the Heinrich event and hence *Scource et al.* [2000] argue it is to young to be the previous D-O cold event. They believe it shows the different ice mass balance response time of each ice sheet surrounding the North Atlantic due to their varying size. Hence the much smaller British ice sheet responds first and up to a thousand years later the Laurentide ice sheet follows. However, as *Bond et al.* [1997; 1999] suggests that D-O cycles have a frequency of 1,479±532 years, then the precursor event described by *Scource et al.* [2000] which could have been 1000 years before Heinrich event 2, may indeed be the prior D-O cold event.

IV.c. Bipolar Climate Seesaw and Deep Water Circulation

One of the most important finds in the study of millennial-scale climate events is the apparent out of phase climate response of the two Hemispheres [*Blunier et al.*, 1998]. *Blunier et al.* [1998] concluded that Antarctic climate changes were significantly out of step with those in the North Atlantic on the basis of $\delta^{18}O$ data (a proxy for temperature) obtained from the Byrd and Vostok ice-cores. They were able to achieve this by correlating the methane records in the ice cores in both Hemispehere, this has its own inherent problems and drawbacks which are discussed more fully in Section Va. Support for *Blunier et al.* [1998] has been found in well dated deep-sea sediment records and has shown that the sea surface conditions in the tropical and South Atlantic Ocean are out of phase with those in the Northern North Atlantic [*Vidal et al.*, 1999; *Ruhleman et al.*, 1999; *Huls and Zahn*, 2001]. If the climate of the two Hemispheres is out of phase then it suggest the global climate system acts as like a seesaw, with each Hemisphere taking turns to drive the system. This 'bipolar seesaw' can be controlled by the atmosphere [e.g., *Webb et al.*, 1997; *Broecker*, 1998], the ocean [*Stocker*, 1994; 1998], or a combination of these two controls [*Broecker*, 1998]. *Stocker* [1998] suggests a simple mechanical analogue that depicts the ocean behavior as a seesaw driven by either high-latitudinal, or near-equatorial sea-surface perturbations, or both.

The deep ocean is, however, the only candidate for driving and sustaining internal long-term climate change (of hundreds to thousands years) because of its volume, heat capacity, and inertia [e.g., *Labeyrie et al.*, 1992; *Stocker et al.*, 1992; *Weaver*, 1994; *Broecker* 1995, *Keigwin et al.*, 1994, *Shaffer and Bendtsen*, 1994; *Jones et al.*, 1996; *Manabe and Stouffer*, 1988; 1995, 1997; *Rahmstorf*, 1994; 1995; *Rahmstorf et al.*, 1996; *Seidov and Haupt*, 1999; *Seidov and Maslin*, 1996; 1999]. 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 sufficiently cooled that it becomes dense enough to sink into the deep ocean. 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 [e.g., *Schmitz and McCartney*, 1993; *Schmitz*, 1995; *Rahmstorf et al.*, 1996]. Formation in the North Atlantic Deep Water (NADW) can be weakened by two processes: 1) the atmospheric polar front preventing the North Atlantic Drift from travelling so far north which reduces the amount of cooling that occurs and hence its capacity to sink, as happened during the last glacial period, or 2) the input of freshwater in the form of melt-water, river discharge, or increased precipitation. If NADW formation is diminished, the weakening of the warm Gulf Stream would cause colder European winters [e.g., *Broecker*, 1995]. However, the Gulf Stream does not give markedly warmer summers in Europe. So a reduction in the Gulf Stream in itself does not in itself explain why summers also became colder during glacial periods.

In contrast in the Southern Ocean the Antarctic Bottom Water (AABW) is formed in coast polnyas where outblowing Antarctic winds push sea ice away from the continental edge and super cool the exposed surface waters. This leads to more sea ice formation and brine rejection, producing the coldest and saltiest water in the world. AABW flows around Antarctic and penetrates the North Atlantic flowing under the lighter NADW and also the Indian and Pacific Oceans.

For rapid climate chnages to be initiated there must be a trigger for a sudden 'switching off' or a strong decrease in rate of deep water formation in either the North Atlantic or the Southern Ocean; this must be due to a decrease in density or dedensification [*Broecker*, 2000] of surface waters. Such a decrease in density would result from changes in salinity (addition of fresh water from rivers, precipitation, or melt water), and/or increased temperatures [e.g., *Dickson et al.*, 1988; *Rahmstorf et al.*, 1996].

Seidov and Maslin [2000] and *Seidov et al.* [2001 and this volume] have suggested that the asynchrony during *Blunier et al.* [1998] A1 and A2 events (which correspond approximately to H4 and H5 or D-O cycle 8 and 12, see Figure 13) can be explained by variations in relative amount of deepwater formation in the two Hemispheres and thus by the resulting heat piracy. Figure 14 shows from model results of the direction and quantity of heat piracy that occurs during different periods. During modern or interglacial conditions the North Atlantic steals heat from the Southern Hemisphere, this North Atlantic heat piracy (Figure 14) maintains a strong Gulf Stream and prevents ice sheet build-up in the Northern Hemisphere. During a Heinrich event when meltwater is injected into the North Atlantic, heat is transported southward cross the equator (Figure 14). This South Atlantic Ocean counter heat piracy causes the Southern Hemisphere oceans to warm, while the Northern Hemisphere oceans cool (Figure 13.1). When the iceberg armada ceases, the freshwater cap on NADW formation is removed and northward cross-equatorial heat transport kicks in. This North Atlantic Ocean heat piracy warms the Northern Hemisphere while cooling down the Southern Hemisphere (Figure 13.2). If the glacial boundary conditions re-assert themselves, the North and South Atlantic Oceans come back to an almost perfect balance (Figure 13.3).

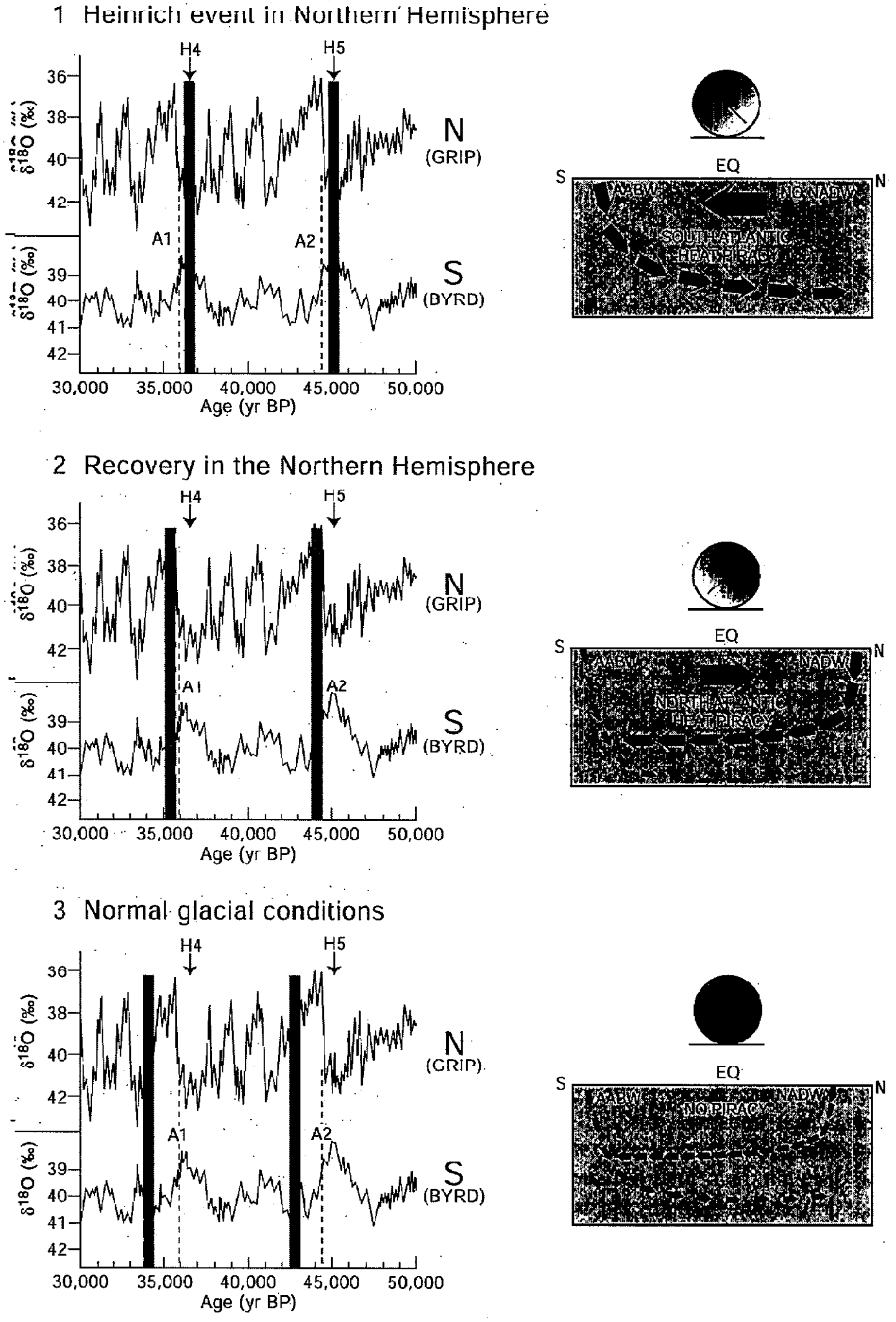

Figure 13. The left panel shows Greenland (GRIP) and Antarctic (Byrd) ice core $\delta^{18}O$ temperature proxy records on the age models generated by *Blunier et al.* [1998]. Three timeslices are shown illustrated on the *Blunier et al.* [1998] records with solid bars; 1. Heinrich event, 2. Northern Hemisphere climate recovery post Heinrich event and 3. Normal glacial conditions. On the right panel is a schematic view of oscillating meridional ocean overturning and associated regimes of heat transports in the Atlantic Ocean. This shows which Hemisphere is controlling the deep water circulation and thus inter-Hemispheric heat transport [adapted from *Seidov and Maslin*, in press].

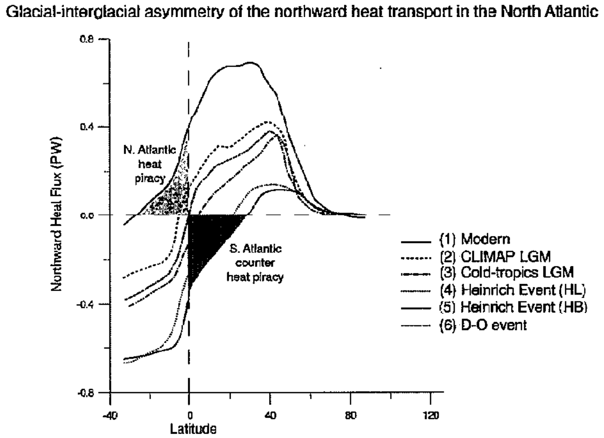

Figure 14. Atlantic Ocean poleward heat transport (positive indicates a northward movement) as given by the ocean circulation model [*Seidov and Maslin* 1999; 2000] for the following scenarios: (1) present-day (warm interglacial) climate; (2) last glacial maximum (LGM) with generic CLIMAP data; (3) "Cold 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 Barrens Shelf Ice sheet or Scandinavian ice sheet; (6) A general Dansgaard-Oeschger (D-O) meltwater event confined to the Nordic Seas. Note that the total meridional heat transport can only be correctly mathematically computed in the cases of either 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.

The most important results of these computer simulations is that these scenarios, does NOT require a substantial change in the heat transported by the upper ocean currents. The imbalance between NADW and AABW productions, i.e. between the deep-ocean flows, is the primary control on cross-equatorial heat transport, and thus could be the sole agent responsible for the observed seesaw climate oscillations. This seems to be counter-intuitive as it is usually assumed that only changes of the upper-ocean currents can affect the heat transport to high latitudes. However *Seidov and Maslin* [1999] and *Seidov et al.* [this volume] suggest that the deep-ocean currents could be the ultimate internal mechanism capable of reversing cross-equatorial heat transport within the required time scale of the oscillations. The simple rule is that when the NADW subsides, the AABW picks up and affects the heat transport regime in the opposite way. Though the model experiments described above a based purely by the input of meltwater into the North Atlantic, *Seidov et al.* [2001; see also this volume] has also demonstrate that the Southern Ocean is also extremely sensitive to meltwater inputs. *Kanfoush et al.* [2000] have clearly shown that there are large iceberg discharges which seem to occur after the Heinrich events. Hence we suggest the true picture of the bipolar seesaw is one driven by both hemispheric sources and that the oscillation of this deep water system may alone be sufficient to explain the 1,500 year glacial and interglacial D-O cycles (see Figure 15).

IV.d. Synthesis

The key to understanding millennial scale fluctuations during glacial periods is not to separate the different events, nor to ignore the role played by the Southern Hemisphere. In attempting to explain the complex patterns of abrupt climate change during the last glacial stage, several important points emerge from recent investigations.

1. D-O cycles are quasi-periodic or irregular in timing (1,500 ± 500years).
2. Heinrich events occur at irregular intervals (7,200 ±2,400 years) and appear to triggered by a threshold mechanism.
3. There is a close and occasionally sensitive interrelationship between the state of ice sheets (i.e., whether relative stable with a frozen base or sensitive to small environmental changes), ocean surface temperature and salinity, deep water formation and sea level.
4. Each of the Northern Hemisphere ice sheets during the last glacial episode have surged or collapsed at different times, thus each has its own independent rhythm of response to internal processes and external forcing [e.g., *Dowdeswell et al.*, 1999].
5. If the bipolar climate seesaw did occur then the deep water system is the most likely candidate to control it (Figure 15).

Having reviewed the possible causes of the Heinrich events and D-O cycles, below we provide our own combined theory (Figure 15). We suggest that the meltwater associated with the D-O cold event could reduces the NADW, which in turns changes the direction of the Hemispheric heat piracy and thus the Southern Hemisphere warms up. This increase warmth in the Southern Hemisphere at some point triggers a melting of sea ice and/or a surging of the Antarctic ice sheets. This reverse the process reducing the AABW and hence strengthening the NADW. This in turn warms the North Atlantic and triggers another D-O melting event. Eventually after a certain number of D-O cycles the sea level rise assocaited with them would be significant to undercut the Laurentide ice sheet, causing a Heinrich event. The Heinrich event would then also influence the Southern Hemisphere and cause a further bipolar

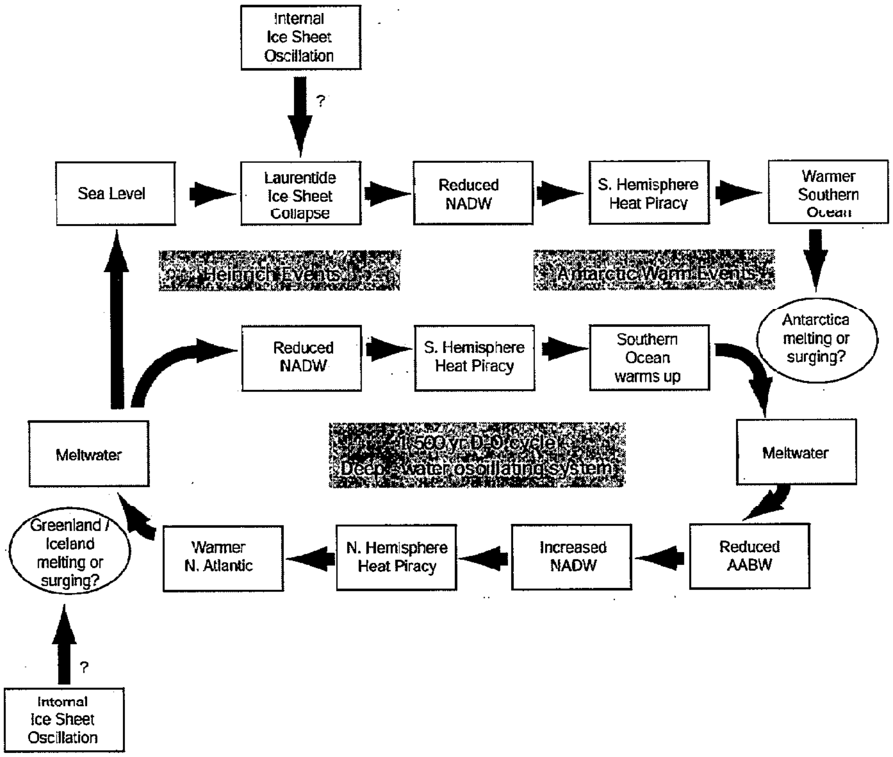

Figure 15. Possible "deep-water oscillatory system" explaining the Glacial and Interglacial Dansgaard-Oeschger cycles [adapted from Maslin and Seidov, submitted]. Meltwater in either the North Atlantic or Southern ocean can start the system going. The meltwater caps the sites of deep water formation in that particular Hemisphere and reduces the deep water formation. This increases heat piracy to the other Hemipshere, which warms that Hemisphere and after hundreds or thousands of years instigates ice sheet melting, thus reversing the whole processes. The system is quasi-periodic because of the oscillatory nature of the system. the stochastic element which is observed in the records [Alley et al., this volume] comes from the different internal dynamics of each ice sheet. The link between the Dangaard-Oeschger ~1,500 year cycles and the Heinrich events is their successive affect on sea level. At a certain point the sea level has risen enough to undercut the Laurentide ice sheet and precipitate a full Heinrich event.

climate swing. Hence once initiated this deep water oscillating system could continue without the need for any external influences.

We can add to this scenario both a stochastic [*Alley et al.*, this volume] and another quasi-periodic element, which is the internal dynamics of the ice sheets (see Figure 15). Which combined with the deep-water oscillating system would produce 1) stable periods when the majority of ice sheet are expanding and 2) occasional periods of very strong instability with episodes of major multiple ice sheet collapse. This seems to be supported by the evidence as the magnitude and timing of each D-O and Heinrich event seem to be different. This combined theory also avoids the pervasive "chicken-and-egg" problem, which is the attempt to interpret geological records to establish precisely which component of the system is the 'instigator' of any one event, and there is of course no need for there to be only one trigger for any specific event.

One key point to note is that global climate seems to be reversible during the D-O cycles, returning to similar conditions to prior to the event (Figure 16). This is not true for the Heinrich events, though each is followed by a climatic rebound in the North Atlantic, each Heinrich events seems to drive global climate towards evermore severe glacial conditions, so we suggest Heinrich events could be one branch of the climate system's bifurcation (Figure 16).

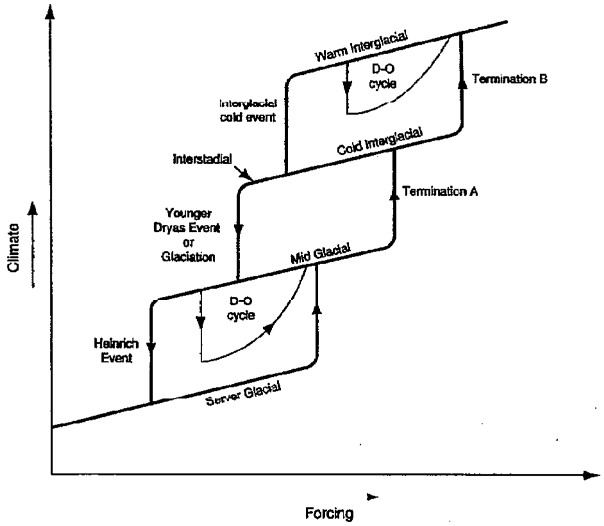

Figure 16. Adaptation of the bifurcation Figure 3 to show the possible relationship between global climate and the forcing factors. Showing that the D-O (Dansgaard-Oeschger) cycles are threshold events but it is relatively easy for the climate system bounce back. In contrast glaciation and Heinrich events are thresholds which require a dramatic change in the forcing to bring the climate back to previous conditions.

V. RAPID CLIMATIC CHANGES DURING THE LAST GLACIAL-INTERGLACIAL TRANSITION

V.a. The Nature of the Last Glacial-Interglacial Transition (LGIT)

The last glacial-interglacial transition (LGIT, ca. 14-9 ^{14}C ka BP) was characterized by a series of extremely abrupt climatic changes [e.g., *Walker*, 1995; *Lowe et al.*, 1994; 1995; 1999; *Alley and Clark*, 1999]. The two most prominent features being rapid warming at 14.7 k GRIP (ss08c chronology, see Lowe et al., in press] ice-core years BP (the start of the "Bølling" episode, or the GI-1 event in the Greenland ice-core isotope stratigraphy of *Björck et al.*, 1998 and *Walker et al.*, 1999] and the well-known period of severe cooling referred to as the Younger Dryas Stadial (GS-1), dated to between 12.7 and 11.5 ka GRIP ice-core yrs BP. These features are easily recognisable in a wide range of proxy records from sites throughout the northern hemisphere [e.g., *Dansgaard et al.*, 1989; *Lowe and Walker*, 1994; *Walker et al.*, in press a; *Alley and Clark*, 1999]. There is also a growing body of evidence which suggests that parts of the Southern Hemisphere may have experienced a broadly similar sequence of climatic events [e.g., *Bard et al.*, 1997; *Bjorck et al.*, 1996; *Alley and Clark*, 1999], including parts of South America [papers in *Sugden*, 2000] and New Zealand [*Denton and Hendy*, 1994]. Some researchers argue that the broadly similar pattern of climate changes inferred from evidence obtained from such widely-separated regions, together with the fact that they approximate the same interval, points to the operation of globally-synchronous climate forcing mechanisms. Others, however, have provided evidence that may imply that at least some of the climate shifts during the LGIT were diachronous across NW Europe [*Coope et al.*, 1998; *Witte et al.*, 1998] and between North America and Europe [*Elias et al.*, in prep.].

According to the GRIP and GISP2 ice-core records [e.g., *Dansgaard et al.*, 1993; *Alley and Clark*, 1999], the sequence of events during the last glacial-interglacial transition was more complex, and the climatic transitions far more abrupt, than had been assumed from prior interpretations based on continental and marine stratigraphical records. For example, a detailed study of the Greenland ice-core records [*Taylor et al.*, 1997] suggests that the transition from the end of the Younger Dryas to the Holocene warm period may have been completed in a series of warming steps lasting no more than a few decades, most probably in less than 50 years [*Alley and Clark*, 1999; *Severinghaus et al.*, 1998]. About half of the warming was concentrated into a single short step that lasted no more than 15 years. By comparison with the abrupt warming at the start of the 'Bølling' and the Holocene, cooling from the warm 'Bølling' to the Younger Dryas appears to have been a more gradual process, involving a series of cooling steps and minor climatic oscillations, extending over a period in excess of 1500 years.

By comparison with ice-core records, the temporal resolution afforded by most continental and/or marine sequences is much more limited, while the problems inherent in the radiocarbon time-scale severely hamper attempts to effect high-precision correlations between the sequences [e.g., *Lowe and Walker*, 2000]. Hence, despite the fact that the sequence and pattern of environmental changes during the LGIT can be reconstructed in much greater detail than is the case for earlier interstadial events [e.g., *Lowe and Walker*, 1994; *Lundqvist et al.*, 1995; *Renssen and Isarin*, 1998; *Coope et al.*, 1998], the vast majority of LGIT records obtained from marine and terrestrial sediment sequences remain inadequate, in terms of their temporal and spatial resolution, for the sorts of scientific questions now being posed. There are notable exceptions, however, where varved sequences have accumulated, which allow reconstructions to be made at decadal to annual-scale resolution [e.g., *Hughen et al.*, 1998, *Litt et al.*, in press] and *Von Grafenstein et al.*, 1999]. In these instances, the rates of environmental change are comparable with those suggested by the ice-core records, but the degree to which these were synchronous with events in the ice-core records is difficult to establish.

The extent to which abrupt climate shifts during the LGIT were globally synchronous, or not, is pivotal to our understanding of global climate mechanisms, not only for this particular period, but also for the earlier episodes of abrupt climatic change, such as D-O and Heinrich events (see Section IV). A major debate has emerged on the subject, which revolves around whether short-term changes in oceanic circulation or in atmospheric gas content constituted the main driving force behind the short-lived climatic perturbations that characterized the LGIT. Central to the argument are detailed comparisons between the Antarctic and Greenland ice cores, which are the most detailed palaeoclimatic archives we have available for this period. The ice-core records are 'wiggle-matched' using, for example, methane concentration data, which are assumed to reflect contemporaneous atmospheric values, and to be globally synchronous. Comparisons of independent climatic signals [e.g., stable isotope and snow accumulation data) have generated conflicting ideas about the degree to which climatic changes in Greenland were synchronous with those in Antarctica. Thus, for example, *Blunier et al.* [1998] concluded that Antarctic climate changes were significantly out of step with those in the North Atlantic (Figure 17) on the basis of δ^{18}O data (a proxy for temperature) obtained from the Byrd and Vostok ice-cores. The data suggest that cooling (the Antarctic Cold Reversal) occurred in Antarctica during the period of warming in the North Atlantic region referred to as the 'Bølling-Allerød Interstadial' (or GI-1). They also suggest that the severely cold Younger Dryas (GS-1) Stadial was a period of rapid warming in Antarctica (Figure 17). By contrast, the Taylor Dome δ^{18}O record appears to indicate a sequence of climate changes in Antarctica remarkably coherent with the Greenland Summit ice-core records [*Steig et al.*, 1998; Figure 17). However the stratigraphy used in the *Steig et al.* [1998] work has subsequently been questioned [*Mulvaney et al.*, 2000] putting in doubt their conclusions.

In turn, these comparisons have fuelled speculation about the global mechanisms that could account for either synchronous or non-synchronous inter-hemispheric climate changes. Prominent among the emerging ideas the *Broecker* [1998] suggestion of a 'bipolar seesaw behaviour in thermohaline circulation', discussed above, as a mechanism which explain anti-phase relationships between the two hemispheres. By contrast, *Denton et al.* [1999] argue for synchronous climate shifts between the two hemispheres, driven by changes in atmospheric greenhouse gas content [e.g., methane, carbon dioxide, atmospheric moisture content), which would be more consistent with the suggestions of *Shackleton* [2000].

It is difficult to test these alternative hypotheses robustly, because of the following limitations in the interpretation of the stratigraphical records. (1) The extent to which the ice-sheet palaeoclimatic records are representative of broader, hemispheric climatic changes is difficult to establish, especially for the southern hemisphere, where few detailed records of the LGIT have yet been developed. (2) Correlation between polar ice cores based on synchronous changes in global methane has one major drawback. This is that each ice core has a unique relationship between the age of the ice and the age of the gas it contains. Hence assumptions of temperature of ice formation, ice accumulation and ice thinning function have to be taken into account to model this difference which can be up to thousands of years. This means that the methane record can be moved substantial up or down compared with the ice δ^{18}O 'temperature' record. So in fact both Greenland and Antarctic ice core methane records can be seen as on sliding time scales, and the best estimate of the gas age has then been used to fix the δ^{18}O temperature proxy to infer either synchronous or non-synchronous inter-hemispheric climate changes. (3) 'Wiggle-matching' between stratigraphical records using the assumption that comparable trends in selected proxy data reflect synchronous events is a circular argument. Each record needs to be dated precisely, and independently. (4) There are differences in detail in the chronologies established for the various ice-core records, especially for pre-Holocene intervals [*Lowe et al.*, in press]. (5) Even if it can be established that the polar ice sheets responded in a synchronous manner to some common forcing mechanism during the LGIT, the degree to which this was also the case on the continents and in the oceans needs to be tested, and not simply assumed. While much headway has been made in recent years in developing a rigorous framework for establishing the degree of synchroneity between ice-sheet, marine and continental records in the North Atlantic region [*Peteet*, 1995; *Walker et al.*, in press b; *Lowe et al.*, in press], precise comparisons are not yet possible, due mainly to the problems inherent in the radiocarbon dating of pre-Holocene events.

V.b. Possible Causes of Abrupt Climate Oscillations During the LGIT

What can be said, therefore, about the causes of the very abrupt climatic changes during the LGIT? It has long been thought that deglaciation was dominated by orbitally induced ice sheet reduction resulting in shifts in oceanic circulation, which controlled sea surface temperatures in the North Atlantic through shifting the latitudinal position of the North Atlantic Polar Front [e.g., *Ruddiman et al.*, 1977;

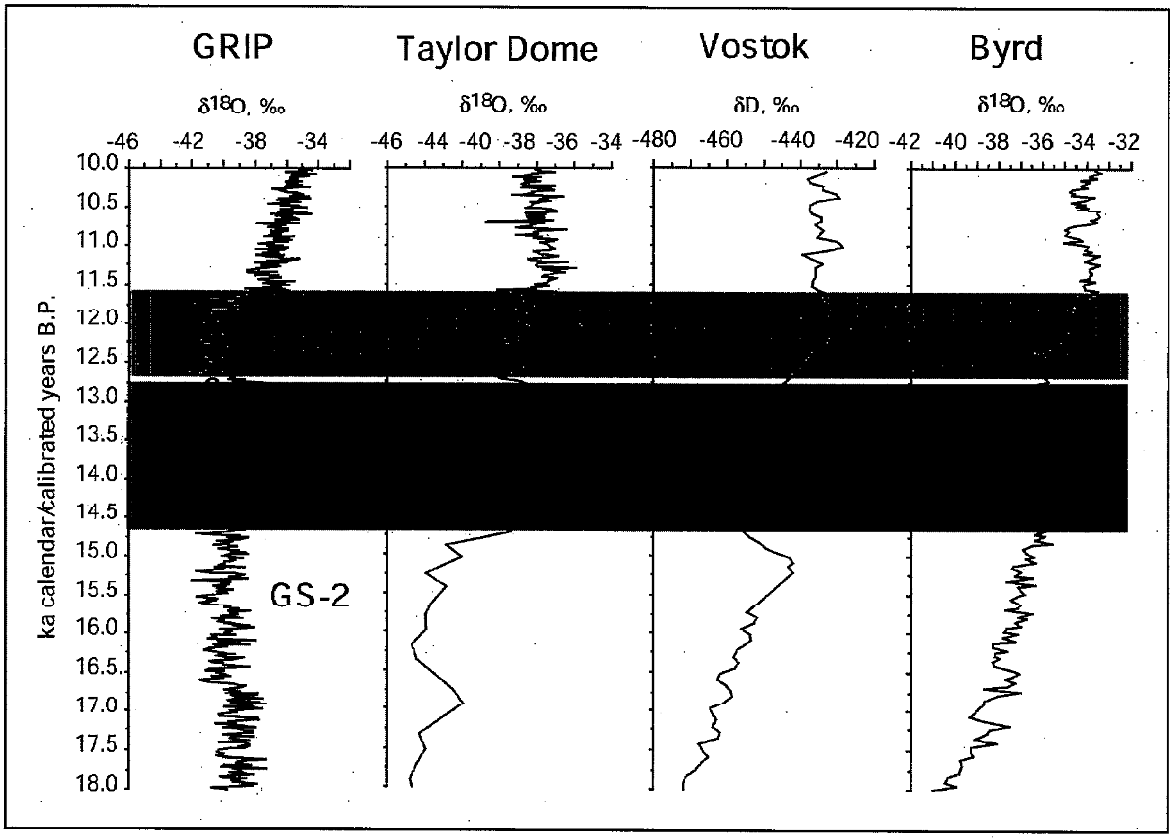

Figure 17. Comparison of the ice core records from the Northern Hemsiphere (GRIP) and the Southern Hemsiphere (Taylor Dome, Vostok and Byrd) for the last glacial-interglacial transition (LGIT). Shaded regions show where it has been suggested that the climate of the North and South Hemisphere was out of phase. GS 1 = Younger Dryas or glacial stadial 1, GI 1 = Bolling-Allerod Interstadial or glacial interstadial 1, GS 2 = glacial stadial 1 and ACR = Antarctic Cold Reversal. It should be noted that the stratigraphy used in the *Steig et al.* [1998] work has subsequently been questioned [*Mulvaney et al.*, 2000] putting in doubt their conclusions that the climate of Antarctic was in phase with Greenland.

Ruddiman and McIntyre, 1981; *Hughen et al.*, 1996]. The colder episodes, especially the very pronounced Younger Dryas cooling [*Dansgaard et al.*, 1989], are then periods imprinted on this trend to warmer interglacial conditions. For example during the Younger Dryas marine records from all parts of the North Atlantic show significant increases in freshwater and ice-rafted debris input. This has led to the suggestion that the Younger Dryas was caused by a sudden influx cold fresh meltwater from the North American and European ice sheets [*Kennett*, 1990; *Bond et al.*, 1992; *Teller et al.*, 1995; *Fronval et al.*, 1995], which was sufficient to cap deep water formation in the North Atlantic. *Berger and Jansen* [1995] suggest it may have only been meltwater diverted through the Gulf of St. Lawrence which was enough to stop deep water formation. It seems almost axiomatic that the driving mechanism for the Younger Dryas episode, for example, must be some form of internal mechanism, such as oceanic circulation change, since this episode of very pronounced cooling occurred at a time of summer radiation maximum in Milankovitch calculations.

The crucial question that remains to be answered, however, is whether these short episodes of cold-water influx not only displaced the North Atlantic Polar Front southwards to bring devastatingly cold conditions to many parts of the northern hemisphere, but also had synchronous cooling effects in the Southern Hemisphere. Or as suggested by the bipolar seesaw theory there should have been a general warming in the Southern Hemisphere. There is, as yet, no clear consensus on this issue, with arguments for and against synchronous inter-hemispheric developments during the LGIT. Further issues that need to be resolved are whether the very short-lived interstadial and stadial episodes that occurred during the LGIT which were triggered by oceanic changes, or by other factors contributed in some way, or even acted as the catalyst for a cascade of changes that brought about significant climatic effects. These contributing or possible controlling factors include the rapid rise in the greenhouse gases, atmospheric carbon dioxide, methane and water vapor, which are known to have been globally synchronized [*Meeker et al.*, 1997; *Fuhrer and Legrand*, 1997].

VI. RAPID CLIMATE CHANGES WITHIN INTERGLACIALS

VI.a. Marine Oxygen Isotope Stage 5e (the Last Interglacial)

The last interglacial (also called the Eemian in Europe) has often been viewed as a close counterpart of the present (Holocene) interglacial stage: sea surface temperatures were similar, and sea level and atmospheric carbon dioxide levels were possibly higher than pre-industrial times [e.g., *Imbrie and Imbrie*, 1992; *Linsley*, 1996]. Assuming that there is a general similarity between these two warm periods, the Eemian has been used to predict the duration of the present interglacial, and also to study the possibility of sudden climate variability occurring within the next few centuries or millennia. However, it has been shown that during the Holocene and the Eemian both the orbital forcing [e.g., *Berger and Loutre*, 1989] and the climate response such as deep water circulation [e.g., *Duplessy et al.*, 1984] were different. Hence many new studies have concentrated on Marine Oxygen Isotope 11, as a possible analogue for the Holocene since it had very similar orbital characteristics to the Holocene.

VI.b. Controversy Over the Timing of the Last Interglacial.

The Eemian or Marine oxygen Isotope Stage (MIS) 5e interglacial (Fig. 18) began sometime between 130-140 ka [e.g., *Martinson et al.*, 1987; *Sarnthein and Tiedemann*, 1990; *Sowers et al.*, 1993; *Szabo et al.*, 1994; *Stirling et al.*, 1995; *Kukla*, 2000] with a warming phase (of uncertain duration) taking the earth out of an extreme glacial phase, into conditions warmer than today [*Frenzel et al.*, 1992]. Warming into the Eemian may have occurred in two major steps, similar to the last deglaciation [*Sarnthein and Tiedemann*, 1990; *Seidenkrantz et al.*, 1993; 1996].

Though it was named after a warm-climate phase seen in the terrestrial pollen record of the Netherlands [e.g., *Zagwijn*, 1963, 1975], the first generally accepted numerical dates for the start of the Eemian came from astronomic tuning of benthic foraminiferal oxygen isotope data [e.g., *Shackleton*, 1969; *Martinson et al.*, 1987]. The age and duration of the warm Stage 5e, however, is still under discussion [*Frenzel and Bludau*, 1987; *Kukla*, 2000]. Work on deep-sea sediments [*Imbrie et al.*, 1993; *Sarnthein and Tiedemann*, 1990; *Maslin et al.*, 1998b] and corals [*Szabo et al.*, 1994; *Stirling et al.*, 1995; *Slowey et al.*, 1996] suggests that rapid warming could have started as early as 132 ka, while work on the Antarctic Vostok ice core suggests a possible initiation at 134 ka [*Jouzel et al.*, 1993; 1996]. Studies of an Alaskan site (the Eve Interglaciation Forest Bed) suggest that the warming probably postdates 140 ka, because a tephra layer, which is thought to underlie this bed, has been dated to 140 +/-20 ka BP, though the precise relationship between the tephra and the organic bed, and of the age of the organic sediments, remains uncertain [*S. Elias*, pers. comm.]. Uranium-Thorium dated records from a continental karst sediment in the southwestern USA [Devil's Hole; *Winograd et al.*, 1988; 1992; 1997], however, suggest a much earlier start of warming at about 140 ka.

There has been much discussion about the reliability of dating of the marine isotope stages when compared with the Devil's Hole record [e.g., *Imbrie et al.*, 1993], but new radiometric Protactinium-231 dating has apparently confirmed that both records are reliable [*Edwards et al.*, 1997]. We must thus consider the possibility that warm conditions did not last for the same amount of time throughout the world. For instance, comparison of various land records suggests that warming may have occurred at different times in the Alps and in northern France [*de Beaulieu and Reille*, 1989].

Winograd et al. [1997] date the ending of the warm period at about the same time as that suggested by the SPECMAP time scale, which means that the duration of the Eemian warm period according to the Devil's Hole record was significantly longer than that suggested by the marine record (25 ka vs. 17 ka). We need to consider the possibility that warm intervals as seen in pollen records have a longer duration than periods of high sea level and low ice volume in the marine record: *Kukla et al.* [1997; 2000] and *Tzedakis et al.* [1997], for instance, suggest that the Eemian (as reflected in the pollen records) started at about 130 ka, but ended much later than the end of MIS 5e, and that the duration of land interglacials thus is indeed longer than the period of low ice volume.

If the complexity outlined above is accepted, then it seems that for thousands of years warm 'interglacial' type conditions in the mid-latitudes on land could have been occurring at the same time as much colder ocean conditions and expanded Arctic ice sheets. If so the Eemian, it appears, could have been a strange beast quite unlike our present interglacial phase, which began with a rapid and largely simultaneous warming all around the world. This confusion over the nature and duration of the Eemian adds to the difficulty in making simple, general comparisons with our present interglacial, and in interpreting the significance of some of the events seen in the marine and ice core records.

VI.c. Evidence of Climate Instability During the Eemian

Initial evidence from the GRIP ice core [*Dansgaard et al.*, 1993; *Taylor et al.*, 1993] suggested that the Eemian was punctuated by many short-lived extreme cold events. The cold events seemed to last a few thousand years, and the magnitude of cooling was similar to the difference between glacial and interglacial. Furthermore, the shifts between these warm and cold periods seemed to be extremely rapid, possibly occurring over a few decades or less.

A second ice core (GISP2) from the Greenland ice cap [*Grootes et al.*, 1993] provided an almost identical climate record for the last 110 ka, shortly after the end of the Eemian. GISP2 also contains marked changes in the isotope values throughout the deeper section that are not consistent with the GIRP record [*Grootes et al.*, 1993]. Significantly, in GISP2 steeply inclined ice layers occur in this lower portion of the core, indicating that the ice has been disturbed, and that we cannot distinguish simple tilting from folding or slippage that would juxtapose ice of very different ages [*Boulton*, 1993]. For this reason, the deeper GISP2 record has been interpreted as containing interglacial and glacial ice of indeterminate age, due to the effects of ice tectonics [*Grootes et al.*, 1993; *Alley et al.*, 1997a]. It has been confirmed that the deeper parts of the GRIP ice core record (referred to above), including the crucial Eemian sequence, also tilted [e.g., *Grootes et al.*, 1993; *Taylor et al.*, 1993; Boulton, 1993; *Chapellaz et al.*, 1997; *Hammer et al.*, 1997; *Steffensen et al.*, 1997], with *Johnsen et al.* [1995, 1997] reporting layers tilted up to 20° within the Marine Isotope Stage 5c (110 ka).

Evidence to support for the occurrence of cold Eemian events was obtained from lake records from continental Europe [*de Beaulieu and Reille*, 1989, *Guiot et al.*, 1993], in particular the Massif Central in France [*Thouveny et al.*, 1994] and Bispingen inGermany [Field et al. 1994]. However, these records suggest only that the Eemian climate was more variable than that of the Holocene, not the more extreme departures to near-glacial conditions seemingly indicated by the ice cores records. Oceanic records from the North Atlantic [*McManus et al.*, 1994; *Adkins et al.*, 1997; *Oppo et al.*, 1997; *Chapman and Shackleton*, 1999] and the Bahamas Outer Ridge [*Keigwin et al.*, 1994] indicate very little or no climatic variability during the Eemian, but a cooling appears to be present in oceanic records from the Sulu Sea [Indonesia; Linsley 1996]. In contrast to this, records from both the Nordic Seas and west of Ireland show a cooling and freshening of the North Atlantic in the middle of the Eemian somewhere between 120 and 123 ka [*Cortijo et al.*, 1994; *Fronval and Jansen*, 1996]. These Nordic records show highly variable surface water conditions throughout the Eemian period. Records from slightly further south on the north-west European shelf sediments, suggest a similar picture of cold intervals during the Eemian [*Seidenkrantz et al.*, 1995].

Evidence for a single sudden cool event during the Eemian is also present in pollen and lake records in central Europe [*Field et al.*, 1994; *Thouveny et al.*, 1994], from loess sedimentology in central China [*Zhisheng and Porter*, 1997] and from ocean sediment records from the eastern sub-tropical Atlantic [*Maslin et al.*, 1996; 1998b; *Maslin and Tzedakis*, 1996] and the re-interpretation of the Nordic Sea records [*Cortijo et al.*, 1994; *Fronval and Jansen*, 1996] by *Maslin and Tzedakis* [1996]. Further support for the existence of an intra-Eemian cooling event comes indirectly from coral reef records. High precision U-series coral dates from western Australia indicate that the main global episode of coral reef building during the last interglacial period (dated between 130 and 117 ka) was confined to just a few thousand years between 127 to 122 ka [*Stirling et al.*, 1995], thus ending at the beginning of the Intra-Eemian cold event at about 122 ka (Figure 18). There is also supporting evidence for a cold dry period between 120-121 from a high precision U-series dated speleothem from NW England [*Hodge*, 2000].

Overall, there is a growing consensus that there was for at least one cold dry event near the middle of the Eemian, at about 120-122 ka. It is characterized by a change in circulation patterns in the North Atlantic, decline in Atlantic surface temperatures by several degrees, and by opening up of the west European forests to give a mixture of steppe and trees. This intra-Eemian cold phase was less dramatic than had been suggested by the variability in the ice core records, but still a major climatic change. Evidence from a high resolution marine core record at Site ODP 658 [*Maslin and Tzedakis*, 1996] suggests that this event may have been driven by a brief reduction in NADW formation (Figure 18). Afterwards climate recovered, but conditions did not return to the full warmth of the early Eemian 'optimum'. We could view this two stage Interglacial in terms of bifurcation as the intra-Eemian cold drives the climate system into a cooler phase which it can not get out because insolation is already dropping (Figure 19).

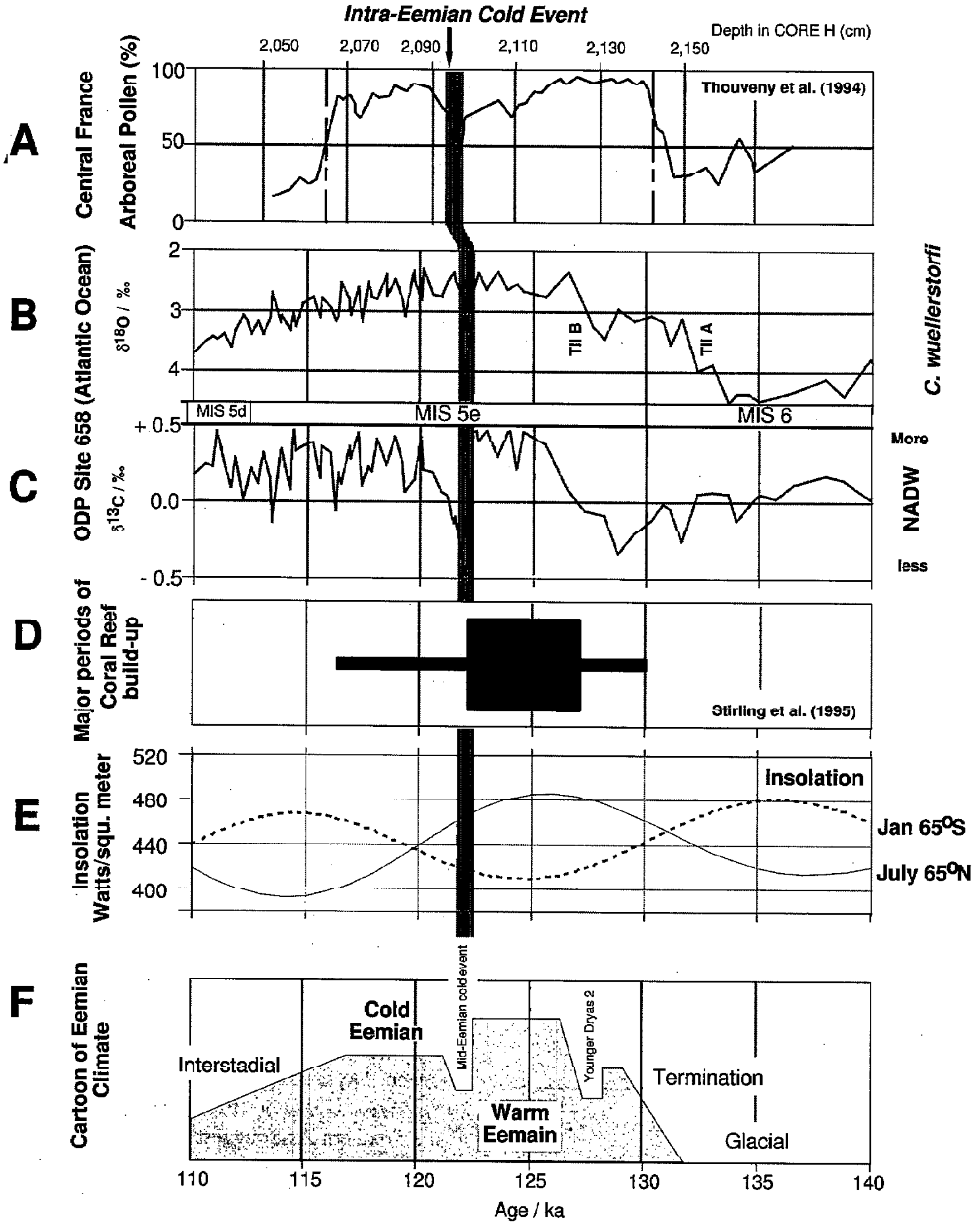

Figure 18. Comparison for key records of Marine Oxygen Isotope Stage 5e. Shaded bar illustartes the possible Mid-Eemian cold event in the records. A summary cartoon illustrating the major changes in climate between 135 ka and 110 ka is given at the bottom [adapted from *Adams et al.*, 1999].

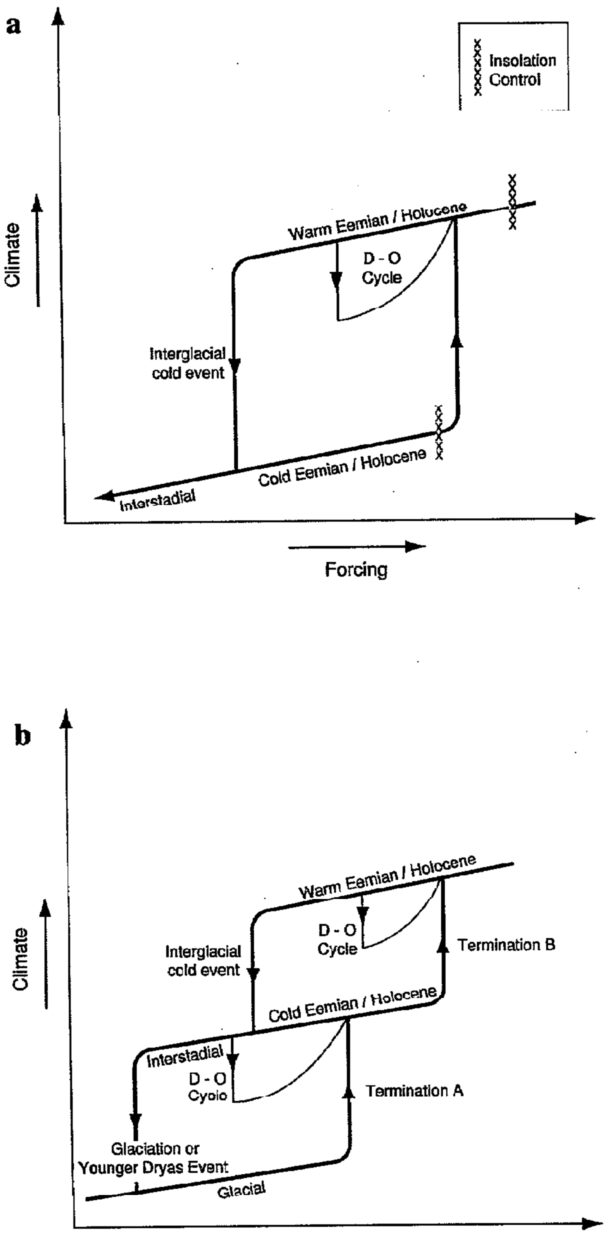

Figure 19. Adaptation of the bifurcation Figure 3 to show the possible relationship between global climate and the forcing factors. A) Shows the possible relationship between a significant Interglacial cold event and the insolation control as an explanation for mild beginnings but colder ends of interglacial periods, see Figure 18. B) Extension of A) to include the Terminations, and Younger Dryas – type events.

VI.d. Holocene

The ice-core records initially suggested the Holocene to be largely complacent as far as climate variability is concerned [e.g., *Dansgaard et al.*, 1993]. This view is being progressively eroded. Long-term trends indicate an early to mid-Holocene climatic optimum with a cooling trend in the late Holocene. Superimposed on this are several distinct oscillations or climate steps which appear to be of widespread significance (8.2 ka, 5.5-5.3 ka and 2.5 ka) see Figure 20. These events now seem to be part of the millenial scale quasi-periodic climate changes, similar to the D-O cycles, and are characteristic of the Holocene [*O'Brien et al.*, 1996; *Bond et al.*, 1997; *Bianchi and McCave*, 1999; *deMenocal et al.*, 2000; *Giraudeau et al.*, 2000].

The periodicity of these Holocene D-O cycles is the subject of much debate. Initial analysis of the Greenland ice core and North Atlantic sediment records have found cycles at approximately the same 1,500 (±500) year rhythm as that found for the last glacial period [*O'Brien et al.*, 1996; *Mayewski et al.*, 1997; *Bond et al.*, 1997; *Campbell et al.*, 1998; *Bianchi and McCave*, 1999; *Chapman and Shackleton*, 2000]. Subsequent analyses have also found both a strong 1,000 year and 550 year cycle [*Chapman and Shackleton*, 2000]. These short cycles have also been recorded in the residual Δ14C data derived from dendrochronology calibrated bidecadal tree-ring measurements spanning the last 11,500 years. The general conclusion is that the Holocene does contain climate variations on the millennial-scale. In general, the coldest points of each of the Holocene millennial-scale cycles surface temperatures of the North Atlantic were about 2-4 °C cooler than at the warmest part [*Bond et al.*, 1997; *deMenocal et al.*, 2000].

The first Holocene event at 8200 ka is the most striking sudden cooling event during the Holocene [*Bjorch et al.*, 1996], giving widespread cool, dry conditions lasting perhaps 200 years before a rapid return to climates warmer and generally moister than the present. This event is clearly detectable in the Greenland ice cores, where the cooling seems to have been about half-way as severe as the Younger Dryas-to-Holocene difference [*Alley et al.*, 1997a; *Mayewski et al.*, 1997]. Records from North Africa across Southern Asia suggest more arid conditions involving a failure of the summer monsoon rains [e.g., *Sirocko et al.*, 1993]. Cold and/or aridity also seems to have hit northern most South America, eastern North America and parts of NW Europe [*Alley et al.*, 1997a and b].

In the middle Holocene at approximately 5,500 ka there seems be a sudden and widespread shift to drier or moister conditions [e.g., *Dorale et al.*, 1992]. The dust and SST records off NW Africa shows that the African Humid Pe-

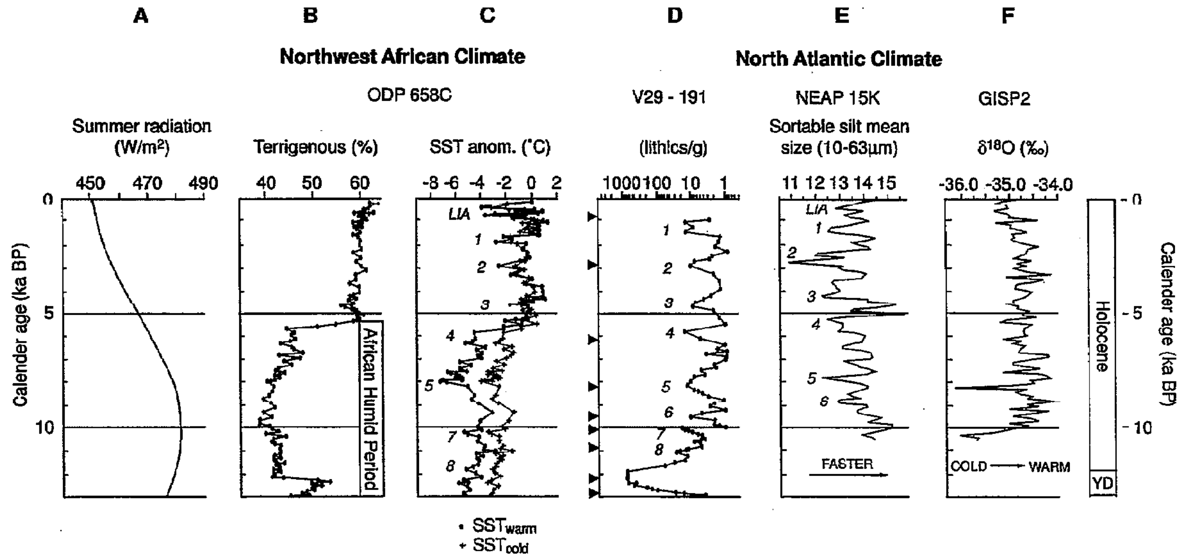

Figure 20. Comparison of summer insolation for 65°N, with Northwest African climate [*deMenocal et al.*, 2000] and North Atlantic climate [V29-191, *Bond et al.*, 1997; NEAP 15K, *Bianchi and McCave*, 1999; *GISP2, O'Brien et al.*, 1995]. Note the similarity of events labeled 1 to 8 and the Little Ice Age (LIA).

riod, when much of subtropical West Africa was vegetated, lasted from 14.8 to 5.5 ka [*deMenocal et al.*, 2000, see Figure 20]. At 5.5 ka there is a 300 year transition to much drier conditions in West Africa (Figure 20). This mid-Holocene shift also corresponds with the decline of the elm (*Ulmus*) in Europe at about 5700 ka and hemlock (*Tsuga*) in North America about 5300 ka. Both vegetation changes were initially attributed to specific pathogen attacks [*Rackham*, 1980; *Peglar*, 1993], but they may be more connected to climate deterioration [*Maslin and Tzedakis*, 1996]. This step to colder and drier conditions could also correspond to the similar change that is observed in the MOIS 5e (Eemian) records. There is also evidence for a strong cold and arid event occurring about 4 ka across the North Atlantic, northern Africa and southern Asia [*Bradley and Jones*, 1992; *O'Brien et al.*, 1996; *Bond et al.*, 1997; *Bianchi and McCave*, 1999; *deMenocal et al.*, 2000; *Cullen et al.*, 2000, see Figure 20]. This cold arid event coincides with the collapse of a large number of the major urban civilizations including: the Old Kingdom in Egypt, the Akkadian Empirer 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 [*Peiser*, 1998; *Cullen et al.*, 2000]. Hence these relatively small changes in Holocene climate may have had immense influence on humanity.

VI.e. Little Ice Age (LIA)

The most recent Holocene D-O cold event is the Little Ice Age. This event is really two cold periods, the first of these cold periods follows the 1000 year long Medieval Warm Period and is often referred to as the Medieval Cold Period (MCP) or LIA b [*deMenocal et al.*, 2000]. The MCP played a role in extinguishing Norse colonies on Greenland and caused famine and mass migration in Europe [e.g., *Barlow et al.*, 1997]. It started gradually before 13th century and ended in the middle of the 17th century [*Bradley and Jones*, 1992]. There was then brief respite and a return to milder conditions. Then the second cold period kicked in, this is more classically referred to as the Little Ice Age [*LIA* b, *deMenocal et al.*, 2000] and lasted from the middle of the 18th century to the end of the 19th century. It is thought that the Little Ice Age may have been the most rapid and largest change in the climate of the North Atlantic region during the Holocene according to ice core and deep sea sediment records [*O'Brien et al.*, 1996; *Mayewski et al.*, 1997; *deMenocal et al.*, 2000]. The Little Ice Age events are characterized by a drop of 0.5-1°C in Greenland temperatures [*Dahl-Jensen et al.*, 1998] and sea surface temperature drop of 4°C off the coast of west Africa [*deMenocal et al.*, 2000] and 2°C off the Bermuda Rise [*Keigwin*, 1996]. One question that still remains to be answered is whether the Little Ice Age was a global

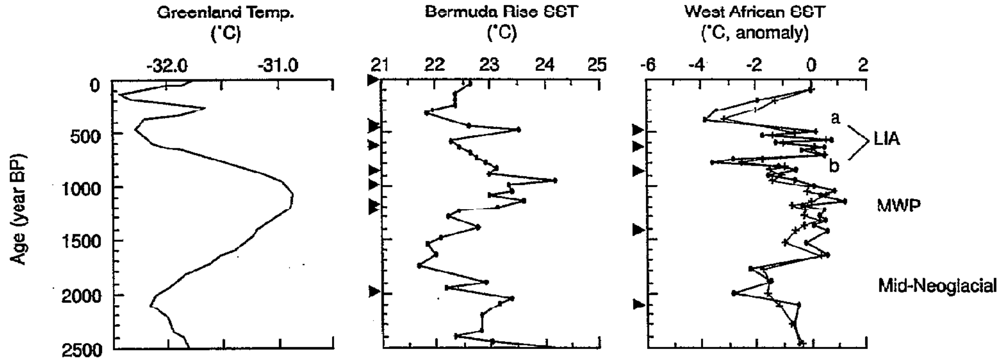

Figure 21. Comparison of Greenland temperatures, the Bermuda Rise sea surface temperatures [*Keigwin*, 1996] and west African and a sea surface temperature [*deMenocal et al.*, 2000] for the last 2.5 ka. LIA = Little Ice Age, MWP = Medieval Warm Period. Solid triangles indicate radiocarbon dates.

or only North Atlantic climate change [*Thompson et al.*, 1986; *Bond et al.*, 1999].

VI.f. Possible Causes of Millennial Climate Fluctuations During Interglacials

Bianchi and McCave [1999] have shown that during the Holocene there have been regular reductions in the intensity of NADW which they link to the Dansgaard-Oeschger cycles identified by *O'Brien et al.* [1995] and *Bond et al.* [1997]. Dansgaard-Oeschger cycles [*Hodge*, 2000] and a major cold event have also been found in the previous interglacial [*Maslin et al.*, 1998b]. There are two possible reasons for the millennial scale changes observed in the intensity of the NADW, instability solely in the North Atlantic region or the bipolar climate seesaw.

First there could be an intrinsic millennial instability in the North Atlantic region. Hence, the amount of freshwater input into the surface waters varies on the millennial time scale to produce the observed reductions. There are a number of possible reasons for this including 1) internal instability of the Greenland ice sheet producing periods of enhanced amounts of melting icebergs, 2) cyclic increases in precipitation over the Nordic Seas due to the North Atlantic storm tracks penetration further north 3) freshwater pulses from the Labrador Sea or 4) changes in surface currents allowing a great import of fresher water from the Pacific, possibly due to reduction in sea ice in Arctic Ocean.

The second possible cause is that the suggested glacial intrinsic millennial-scale bipolar seesaw also operates during interglacial periods (see Figure 15). *Seidov et al.* [2001; this volume) demonstrate that the deep water oscillator described in Figure 15 could be just as valid for interglacial periods. We suggest this is the most plausible explanation at present because the similarity of the events in the Holocene are similar to those in the last glacial period. The defining evidence that is still missing is an out of phase relationship between the climate records of the North Atlantic and the Southern Ocean during the Holocene.

On a more radical note *Wunsch* [2000], provides a very different explanation for the pervasive 1500 year cycle seen in both deep sea and ice core, glacial and interglacial records. *Wunsch* [2000] 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. As the 1500 year peak appears precisely at the period predicted as a simple alias of the seasonal cycle inadequately (under the Nyquist criterion) sampled at integer multiples of the common year. When *Wunsch* [2000] removes this peak from the Greenland ice core data [*Mayewski et al.*, 1997] and deep-sea spectral records [*Bianchi and McCave*, 1999] 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 data set may not represent the true occurrence of the millennial scale events in the record. It also supports the case that both Heinrich events and Dansgaard-Oeschger cycles are quasi-periodic with many different and possibly stochastic influences on their occurrence.

THE FUTURE

Future Dramatic Decadal Time-scale Climate Transitions?

From present understanding of Quaternary climate change, we know there are certainly large climatic transitions which have occurred on the time-scale of individual human lifetimes. For example the end of the Younger Dryas and various D-O cold events during the Holocene. Many other substantial shifts in climate took at most a few decades or centuries (Heinrich events, various stages during the last deglaciation). It is clear that despite a huge amount of data being produced there are still many problems with understanding the mechanisms controlling century to millennial scale global climate changes [e.g., *Rind and Overpeck*, 1993, see Figure 22]. The most important finding of this synthesis, however, is the fundamental importance of the deep-water system in controlling rapid global climatic change. Ours is a unique system as the NADW only developed during the Miocene and did not really become important until the closure of the Panama gateway. Since then it has been put forward as a major control on the ONHG, MPR, glacial-interglacial cycles, Heinrich events, glacial and interglacial D-O cycles.

Despite our growing understanding of the causes of rapid climate shift it is still difficult to quantify the future risks of sudden switches in the deep-water system. This is because of the possibility of NADW bifurcation [*Rahmstorf et al.*, 1996] and it is not known where on the threshold figure our current climate system resides (Figure 3). The possibility of deep water variations do appear to be real and relatively small-scale changes in North Atlantic salinity have been observed and studied in the last few decades [*Dickson et al.*, 1988]. Fluctuations in surface water characteristics and precipitation patterns in that region vary on decadal time scales with variations in the strength of high-pressure areas over the Azores and Iceland [North Atlantic Oscillation; *Hurrell*, 1995, 1996], providing an observed apparent link between salinity and climate fluctuations. The fear is that relatively small anthropogenic changes in high-latitude temperature as a result of increased concentrations of greenhouse gases might effect the Nordic Seas in the following ways: increased precipitation, increased freshwater runoff and/or meltwater from the adjacent continents or reduced sea ice formation [*Rahmstorf et al.*, 1996]. All of which would reduce the surface water salinity and thus the potential to form deep water. Some scenarios in which atmospheric carbon dioxide levels are allowed to rise to several times higher than at present result in increased runoff from rivers entering the Arctic Basin, and a rapid weakening of the Gulf Stream, resulting in colder conditions (especially in winter) across much of Europe [*Broecker*, 1997b].

There is however a second twist, the bipolar seesaw that has been discovered in the palaeoclimate records [*Broecker*, 1998; 2000; *Stocker*, 1998; *Seidov and Maslin*, 2000]. If indeed the NADW formation is reduced in the future cooling the North Atlantic region there could be a corresponding by delayed warming in the Southern Ocean. Recent modeling results, however, also suggest that the Southern Ocean is as sensitive if not more so to meltwater inputs than the North Atlantic region [*Seidov et al.*, 2001; this volume]. Meltwater input to the Southern ocean has been shown to dramatically reduce AABW production and increase deep water temperatures. This in turn would allow the NADW to strengthen warming the Northern Hemisphere. So currently we have two completely opposite scenarios which will make a significant difference to the inter-Hemisphere heat balance, which influences the whole monsoonal system. The only difference is whether global warming causes the most significant freshwater input to occur in the North Atlantic region or the Southern ocean.

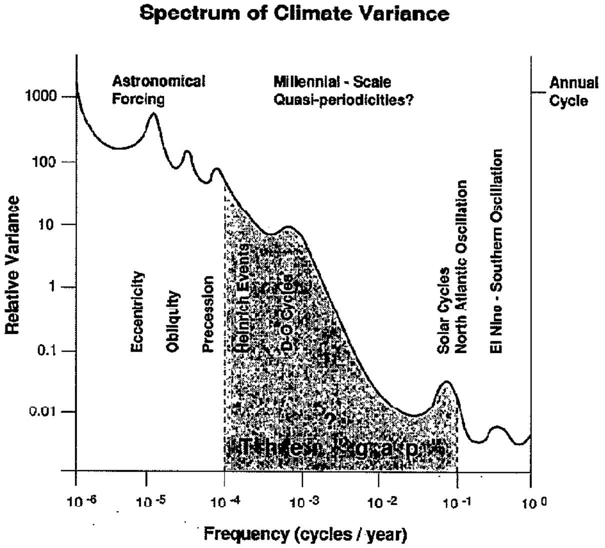

Figure 22. Spectrum of Climate Variance showing the climatic cycles for which we have good understanding and the 'gap' between 100s and 1000s of years for which we still do not have adequate understanding of the causes.

To paraphrase W.S. Broecker; 'Climate is an ill-tempered beast, and we are poking it with sticks'.

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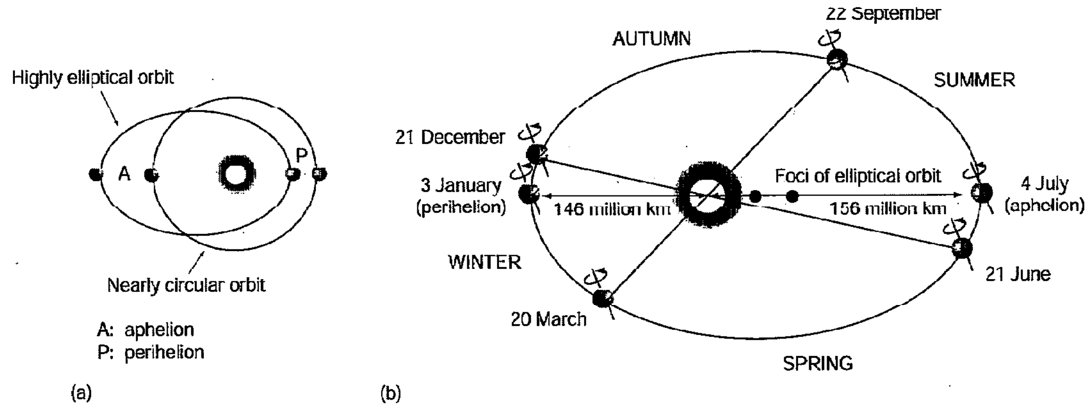

Figure 23. Changes in the shape of the Earth's orbit around the sun. (a) The shape of the orbit changes from a near circular to elliptical. The position along the orbit when the Earth is closest to the Sun is termed the perihelion and the position when it is furthest from the Sun aphelion. (b) The present-day orbit and its relationship to the seasons, solstices and equinoxes [after *Wilson et al.*, 2000].

APPENDIX I: ORBITAL FORCING; THE BASICS [ADAPTED FROM *WILSON ET AL.*, 2000 AND *LOWE AND WALKER*, 2000]

Eccentricity (Figure 23)

The shape of the Earth's orbit changes from near circular to an ellipse over a period of about 100 ka with a long cycle of about 400 ka (in detail there are two distinct spectral peaks near 100 ka and one at 413 ka). Descibed another way the long axis of the ellipse varies in length over time. Today, the Earth is at its closest (146 million km) to the sun on January 3rd: this position is known as perihelion. On July 4th it is at most distance from the sun (156 million km) at the aphelion. Changes in eccentricity cause only very minor variations, approximately 0.03% in the total annunal insolation, but can have significant seasonal effects. If the orbit of the Earth were perfectly circular there would be no seasonal variation in solar insolation. Today, the avaerage amount of radiation received by the Earth at perihelion is ~ 351 Wm^2 reducing to 329 Wm^2 at aphelion, a difference of more than 6%. At times of maximum eccentricity over the last 5 Ma this difference could have been as large as 30%. *Milankovitch* [1949] suggested that the northern ice sheets are more likely to form when the Sun is more distant in summer, so that each year some of previous winters snow can survive. At a certain size the ice sheets start influencing the local climate and there are positive feedbacks which are discussed more fully in Section IIa. As the intensity of solar radiation reaching the Earth diminishes as the square of the planet's distance, global insolation falls at the present time by near 7% between January and July. A situation that is more favouable for snow surviving in the Northern rather than Southern Hemisphere. The more elliptical the shape of the orbit becomes, the more the season will be exaggerated in one hemisphere and moderated in the other. The other effect of eccentricity is to modulate the precession effects, see below.

Obliquity (Figure 24)

The tilt of the Earth's axis of rotation with respect to the plane of its orbit (the plane of the ecliptic) varies between 21.8° and 24.4° over a period of 41 ka. It is the tilt of the axis of rotation that gives us the seasons. Because in summer the hemisphere is tilted towards the Sun and is warmer because it recieves more than 12 hours of sunlight and the Sun is higher in the sky. At the same time the opposite hemisphere is tilted away from the Sun and is in winter as it colder as it recieves less than 12 hours of sunlight and the Sun is lower in the sky. Hence the greater the obliquity the greater the difference between summer and winter. As *Milankovitch* [1949] suggested the colder the Northern Hemisphere summers the more like ice sheets are to build-up. This is why there seems to be a straight forward explaination for the glacial-interglacial cycle prior to the Mid-Pleistocene Revolution wheich occur every 41 ka.

Precession (Figure 24)

There are two components of precession: that relating to the elliptical orbit of the Earth and that related to its axis of rotation. The Earth's rotational axis moves around a full

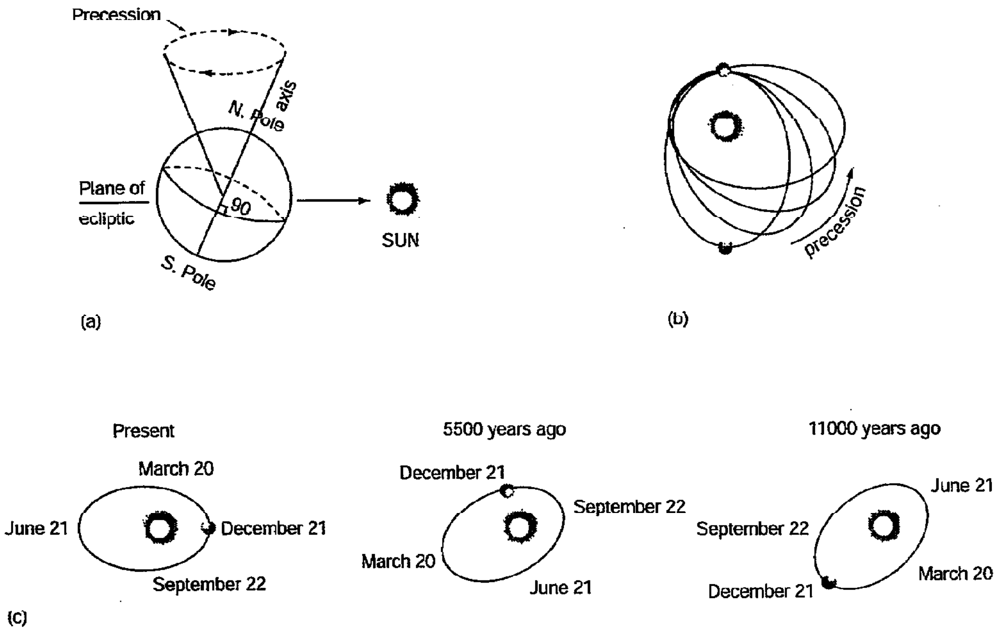

Figure 24. The components of the precession of the equinoxes. (a) The precession of the Earth's axis of rotation. (b) The precession of the Earth's orbit. (c) The precession of the equinoxes [after *Wilson et al.*, 2000].

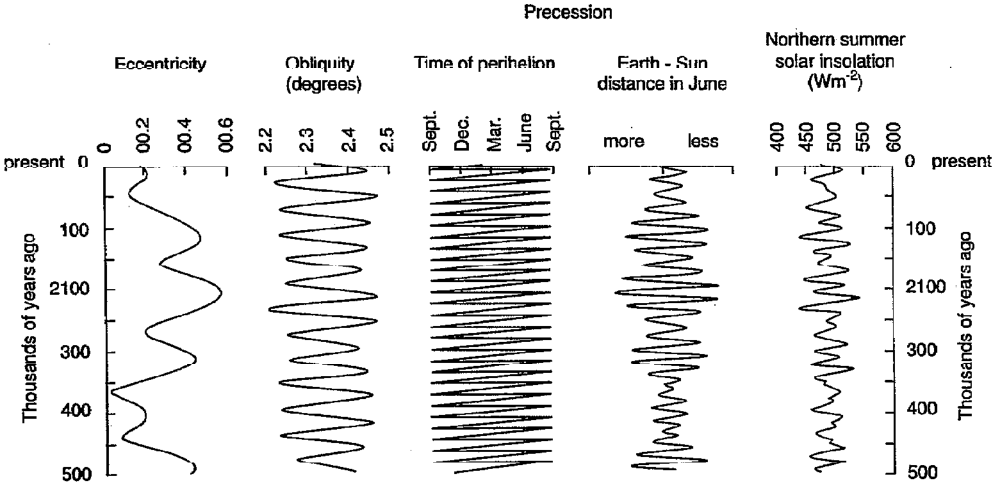

Figure 25. Variations in the Earth's orbital parameters: eccentricity, obliquity and precession and the resultant Northern Hemisphere 65°N insolation for the last half million years [after *Wilson et al.*, 2000].

circle, or precesses every 27 ka (Fig 24 a). This is similar to the gyrations of the rotational axis of a toy spinning top. Precession causes the dates of the equinoxoes to travel around the sun resulting in a change in the Earth-Sun distance for any particular date, for example Northern Hemisphere summer (Fig. 24 c). While the precession of the Earth's orbit is shown in Figure 24 c, which has a periodicity of 105 ka and changes the time of year when the Earth is closest to the Sun (perihelion).

It is the combination of the different orbital parameters that results in the classically quoted precessional periodicities of 23 ka and 19 ka. Combining the precession of the axis of rotation plus the precessional changes in orbit produces a period of 23 ka. Combining the shape of the orbit i.e., eccentricity, and the precession of the axis of rotation results in a period of 19 ka. These two periodicities combine so that perihelion coincides with the summer season in each hemisphere on average every 21.7 ka, resulting in the precession of the equinoxes.

Combining Eccentricity, Obliquity and Precession (Figure 25)

Combining the effects of eccentricity, obliquity and precession provides the means of calculating the insolation for any latitude back through time [e.g., *Milankovitch*, 1941; *Berger*, 1976; 1979; 1988; 1989; *Berger and Loutre*, 1991]. The maximum change in solar radiation in the last 600 ka (see Figure 25) is equivalent to reducing the amount of summer radiation received today at 65°N to that received now over 550 km to the north at 77°N. Which in simplistic terms brings the current glacial limit in mid-Norway down to the latitude of Scotland. However, the key factor to note is that each of the orbital parameters has a different effect with changing latitude. For example obliquity has increasing influence the higher the latitude, while precession has its largest influence in the tropics.

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