Challenges to our understanding of the general circulation: abrupt climate change[1]

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0.1 INTRODUCTION

About 14,700 years ago (14.7kyr BP), towards the end of the last ice age, the climate warmed dramatically and abruptly around the North Atlantic- by as much as the difference between full glacial and interglacial conditions - in no more than a decade or two. This is all the more remarkable because it occurred in the presence of massive ice sheets and continuation of the albedo forcing that presumably had been helping maintain glacial conditions up to that point. But it was not to last. Sometime just after 13kyr BP this Bolling/Allerod wam period ended as climate first cooled, and then abruptly cooled, into the so-called Younger Dryas. As near glacial conditions returned, glaciers advanced around Europe and the forests that had established themselves in the preceding warm epoch died. The Younger Dryas ended with a second abrupt warming, lasting no more than a decade or so, that shifted temperatures back to those of the Holocene and of today.

The idea that the climate system goes through such abrupt shifts did not take the climate research community by storm but dribbled into acceptance in the 1980s and the early 1990s. Only when duplicate ice cores said the same thing and the evidence was found in multiple quantities within the ice - oxygen isotopes, dust concentrations, snow accumulation and so on - and it could be correlated with terrestrial and marine records did acceptance that abrupt climate change was a reality sink in.

This gradual acceptance is telling. When Hays et al. (1976) showed just how well climate records from deep sea cores could be matched to orbital cycles it was deeply satisfying: the gradual waxing and waning of the great ice sheets could be explained by equally gradual changes in the distribution of delivery of solar radiation to the Earth's surface. Insolation over high northern latitudes was deemed to be particularly important with reduction in summer leading to retention of winter snow and ice sheet growth. All that remained was to show exactly how the climate system accomplished the necccesary links.

Almost three decades later we are still far from understanding how orbital changes are converted into ice sheet growth and decay. While this is testimony enough to our limited understanding of the climate system and general circulations, abrupt climate change is now the star witness. In this case the climate changes occurred not only abruptly but, apparently, in the absence of any external forcing. The lack of any theory for how such changes could occur helps explain the gradual acceptance of what the data was saying.

In the succeeding two decades two advances have been made. First the spatial pattern of abrupt climate change has been better delimited and it is now known that these events occurred essentially synchronously across much of the globe within the atmosphere, the surface ocean and the deep ocean. Abrupt changes are not found in the ice records from Antarctica and the southern hemisphere midlatitudes remain a question. These spatial patterns place some severe constraints on proposed mechanisms of abrupt climate change. Second, mechanisms have been advanced that revolve around the thermohaline circulation (THC). Broecker et al. (1985) were perhaps the first to suggest that rapid warmings and cooling of climate around the North Atlantic were caused by rapid switchings on and off of North Atlantic Deep Water formation with 'on' states being associated with transport of warm waters into the subpolar North Atlantic. Despite difficulties explaining the paleoclimate record of abrupt changes with the THC theory, no competing idea has yet been offered.

The paleoclimate record poses many challenges to our understanding of the general circulation of the atmosphere and ocean, of which explaining abrupt change is just one. How orbital changes cause ice sheet growth and decay remains a major unsolved problem but will be probably be solved as it becomes computationally feasible to integrate coupled atmosphere-ocean general circulation models (GCMs) through orbital cycles. It is only in recent years that time snapshot simulations of the Last Glacial Maximum (LGM) with coupled GCMs have become commonplace (Shin et al. 2003, Hewitt et al. 2003). As suggested by Ruddiman and McIntyre (1981), it is probably a solar radiation distribution that allows increased winter export of tropical moisture into higher latitudes, there to fall as snow, and reduced summer insolation at high latitudes, which allows the snow to be retained until next winter, that will cause ice sheets to grow.

Further back in time, evidence of equable climates poses an enormous challenge to our understanding of the general circulation and the climate system. A particularly interesting example is the Eocene, when temperatures of high latitude northern continental interiors remained above freezing in winter, allowing crocodilians to survive in subpolar regions. More recently the greening of the Sahara in the mid-Holocene, when the worlds most impressive desert essentially became a moist savannah, remains a fascinating unexplained problem. Certainly it was triggered by orbital changes that increase summer insolation over the Northern Hemisphere but the apparently abrupt onset and demise of the African Humid Period (deMenocal et al. 2000), and the fact that other northern hemisphere monsoon regions show less impressive changes, suggest a non-local coupling between deserts and monsoons on paleoclimate timescales that is waiting to be elucidated.

Baffling though these problems are, the focus in this article will be on abrupt climate changes in glacial times. We will advance a case for an important role for the tropics in climate change. To begin we will review the evidence for abrupt climate change and summarize the current knowledge of the spatial footprint. We will also review evidence for the relationship between abrupt changes in surface climate and deep ocean circulation. This will form the basis for a critique of the THC theory of abrupt change before we advance a case for a mechanism that involves global atmosphere-ocean coupling and an active role for the tropics. This mechanism will be as sketchy as that of Broecker et al. (1985) but hopefully will inspire some future investigations.

0.2 ABRUPT CLIMATE IN POLAR ICE CORES

The characteristics of abrupt climate change as recorded in polar ice cores from Greenland and Antarctica have been well described by Wunsch (2003). The problem can be seen in Figure 1, which is taken from that paper. The $\delta^{18}O$ content of ice in the Greenland core shows frequent rapid drops and even more dramatic increases throughout the last glaciation. The Younger Dryas appears to have been the most recent of these. The $\delta^{18}O$ content of ice is supposed to be a proxy for the local temperature when the snow fell although it is also influenced by the $\delta^{18}O$ content of the water that was evaporated and then transported to fall over the ice core location. Either way the record shows dramatic climate changes as much as two thirds of the size of the difference between full glacial and interglacial conditions. These changes occurred in decades.

The Antarctic cores do not show any such rapid climate changes. Wunsch (2003) concludes, quite persuasively that the two are uncorrelated on the millennial timescale (but correlated on the glacial-interglacial timescale), although others have suggested more complex relationships between the two (Roe and Steig 2004). The timescale of the Antarctic core was adjusted to bring the methane records, also shown in Figure 1, into agreement on the basis that methane is a well-mixed gas. The fact that this can be done indicates that the source regions for methane, especially in tropical wetlands, were effected by the rapid climate changes (Brook et al. 1999) and that the changes were not simply regional North Atlantic events.

Figure 1

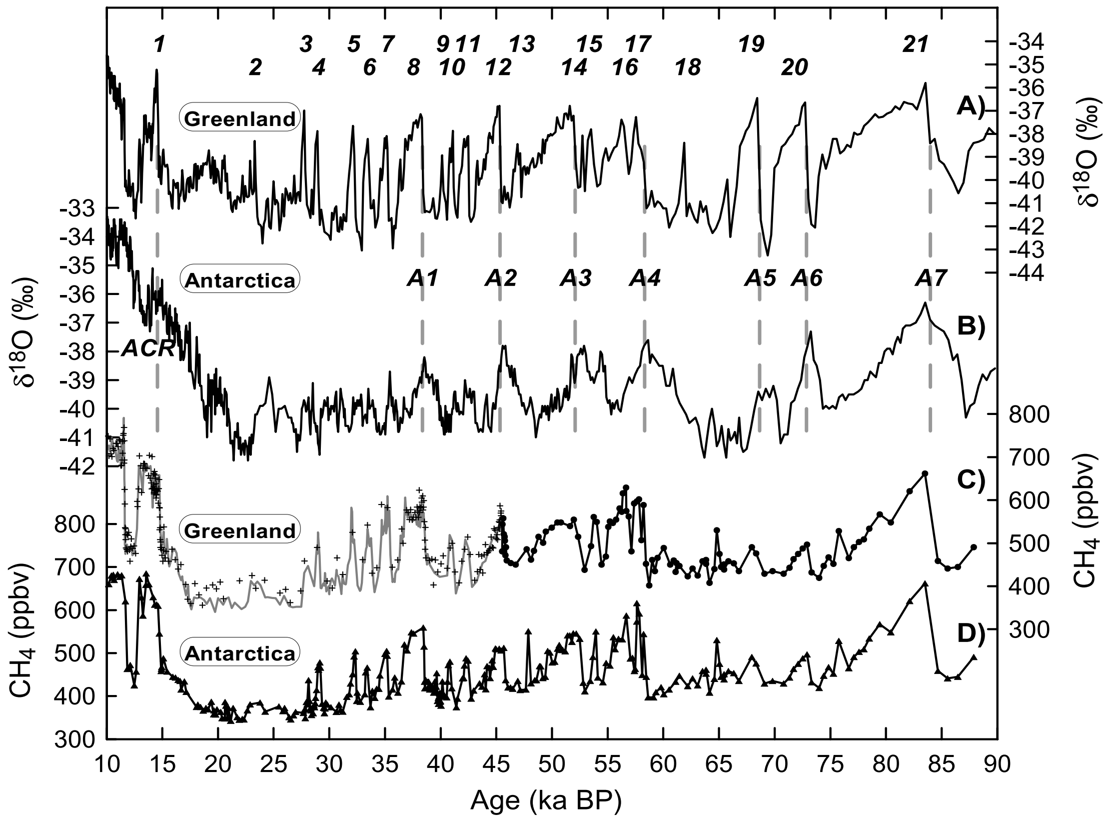

Figure 1 (A) $\delta^{18}O$ in the GISP2 Greenland ice core, (B) $\delta^{18}O$ in the Byrd Antacrtic ice core and, (C) and (D), the methane in the GRIP and GISP2 core and the Byrd core, respectively. The numbers at the top denote Dansgaard-Oeschger events in Greenland and the dashed vertical lines are Antarctic warm events. ACR refers to the Antarctic Cold reversal, a modest cooling during the deglaciation in Antarctica which preceded the Younger Dryas. Taken from Blunier and Brook (2001).

Statistical analysis presented by Wunsch shows to be true what the eye perceives, that the Greenland climate is bimodal, having two preferred states which it switches inbetween. The histograms of $\delta^{18}O$ in the two Greenland cores (GRIP and GISP2) show obvious bimodality whereas the Antarctic core (Byrd) is unimodal, though with a long tail. This is striking evidence of nonlinearity and threshold behavior in the climate system, at least in Greenland. Wunsch suggests that this arises from switching between two different evaporative source regions for the water that falls as snow onto the Greenland core location and can reproduce similar behavior with a two source model, some noise and some simple rules for transitioning between sources.

Even were the two source explanation to be true it implies that the atmospheric circulation is capable of switching between circulation regimes with different trajectories of atmospheric water vapor and condensate between the oceans and Greenland. However it does appear that the original interpretion of the $\delta^{18}O$ in terms of temperature has some validity. Using an entirely independent methodology based on the temperature dependence of the diffusion of gases within the ice core, Severinghaus and Brook (1999) and Severinghaus et al. (1998) deduced temperature changes at the ice surface of as much as $9°C$ in a few decades. This too may be easiest to explain in terms of rapid changes in atmospheric circulation, as we shall see.

The kind of climate change seen in the Greenland ice cores almost perfectly fits Lorenz's description of an 'almost intransitive' system: 'a particular solution extending over an infinite time interval will possess successive very long periods with markedly different sets of statistics' (Lorenz 1968). Lorenz developed this concept of climate change, which seems more relevant today than ever, even before the ice core data was available!

In summary, abrupt climate changes, consisting of coolings followed by rapid coolings and then abrupt warmings, punctuated the entire glacial period at Greenland but no such thing happened in Antarctica. At Greenland there is enticing evidence of nonlinearity of the climate system with thresholds and switches. The Younger Dryas is the most recent of these abrupt changes. Much of the discussion to follow on the spatial and temporal structure of abrupt changes will concern the Younger Dryas, because this is the best observed, but it is anticipated that the descriptions are generally valid for all the abrupt changes.

0.3 ABRUPT CLIMATE CHANGE IN THE SURFACE ATLANTIC OCEAN

Were abrupt climate change limited to Greenland it would not pose too much of a challenge to our understanding of the general circulation. It would be easy to imagine some alteration of the circulation, and movement of heat by stationary and transient eddies, that could accomplish the observed effects. However, as time has gone by, changes elsewhere in the global tropics and northern hemisphere have come to light and these changes appear to be synchronous with those in Greenland. The first evidence was from proxies for sea surface temperature (SST) preserved in ocean bottom sediment cores. Bond et al. (1993) claimed that when Greenland was cold the subpolar North Atlantic SSTs were also cold, although low sedimentation rates made the time resolution of the core too imprecise for easy cross comparison with the Greenland record.

Sachs and Lehman (1999) presented records from the Bermuda Rise, a region of high sedimentation that allows for good temporal resolution. The agreement between the $\delta^{18}O$ proxy for SST and the Greenland record through numerous abrupt climate changes during the last glacial is startling (Figure 2): whenever Greenland is cold, the subtropical North Atlantic Ocean is cold too. While it is true that this conclusion partly depends on the fact that the age control on the Bermuda record was fitted in order to maximize the correspondence between the two records, the fact that it is possible to get such a high correspondence testifies to a real link between climate changes in these two locations.

Lea et al. (2003) used Mg/Ca ratios to reconstruct SSTs above the Cariaco Basin, a region of annually laminated sediments north of Venezuela, during the last deglaciation. They found an abrupt warming at the Bolling/Allerod transition, an abrupt cooling of as much as $4°C$ at the beginning of the Younger Dryas and an abrupt warming at its termination. This result is consistent with Sachs and Lehman and Bond and indicates that the entire North Atlantic surface ocean cooled dramtically during Greenland stadials.

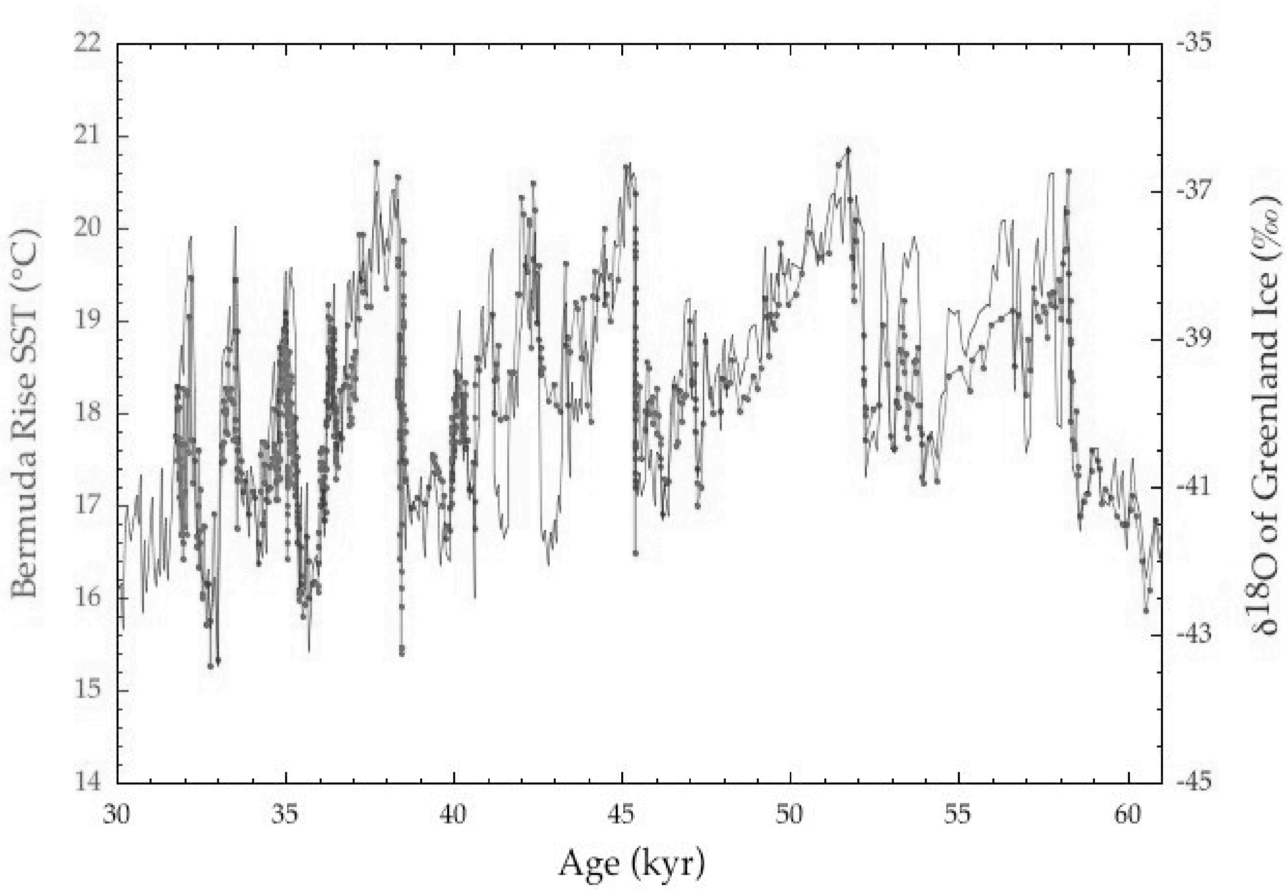

Figure 2 Reconstructed sea surface temperatures based on alkenone unsaturation ratios in sediments on the Bermuda Rise for the period from 30,000 to 60,000 years ago (line with dots, left axis), plotted together with Greenland $\delta^{18}O$ (plain line, right axis) on the GISP2 ice core time scale. Taken from Sachs and Lehman (1999).

0.4 ABRUPT CLIMATE CHANGE AWAY FROM THE NORTH ATLANTIC

0.4.1 The Caribbean and tropical Atlantic

Further south than the Sachs and Lehman record (1999), Hughen et al. (1996, 1998) showed that abrupt climate change also affected the tropical Atlantic. In the Cariaco Basin, just north of Venezuela, sediments reveal a transition into and out of the Younger Dryas as abrupt as that observed in Greenland. These were interpreted as abrupt changes in trade wind strength. Peterson et al. (2000) show that almost all of the abrupt jumps seen in Greenland between 60 kyr BP and 25 kyr BP (and numbered in Figure 1) are also seen in the Cariaco record as shifts in sediment reflectance and major element chemistry. These sediment characteristics record changes in the rate of riverine influx from South America north of the Amazon basin, i.e. the balance of precipitation and evaporation in that region, suggesting that during Greenland cold stadials northern regions of South America received less rain than now. The most obvious way in which this could happen is through a southward shift of the Intertropical Climate Zone (ITCZ). Recent results from speleotherms have indeed indicated that, at times when northern South America was drier, northeast Brazil was wetter (Wang et al. 2004)[1].

0.4.2 Northern extratropics

The Younger Dryas abrupt climate change was first identified in pollen records in northern Europe and is named after a cold tolerant plant that reestablished itself during this time. Throughout Europe mountain glaciers advanced, as in Scandinavia and the Alps, or they re-formed, as in the British Isles (see references in Denton et al. (2005)). Glacial advances require adequate snow in winter and cool enough summers for accumulation to exceed ablation. In North America the record is mixed. Shuman et al. (2002) show that across eastern North America vegetation changed dramatically at the beginning and end of the Younger Dryas but that these cannot simply be accounted for by a cooling, in part because summers may have been warmer as a

[1]The southward shift of the ITCZ during the Younger Dryas is not easy to reconcile with alkenone based SST reconstructions that show warming of the South American coast at $10^\circ N$ (Kim and Schneider 2003) and in the Caribbean Sea (Ruhlemann et al. 1999). Those SST reconstruction also disagree with the Mg/Ca-based ones of Lea et al. (2003) which show dramatic cooling north of Venezuela during the Younger Dryas.

consequence of increased insolation. In western North America alpine glaciers advanced during the Younger Dryas but with notable exceptions in the Sierra Nevada and around Mt. Rainier (Licciardi et al. 2004). Since precipitation patterns are highly spatially variable, the simplest explanation for glacial advances in Europe and North America would be a colder climate, including summers. Together with the Greenland record this suggests that the Younger Dryas abrupt climate change involved cooling across much of the northern extratropics.

Where longer records exist there is obvious correlation with all of the abrupt changes in Greenland during the last glacial. For example these events extended to the northeast Pacific Ocean margin, appearing as changes in ocean oxygenation in the Santa Barbara basin and Gulf of California (Behl and Kennett 1996), although the interpretation of these records in terms of climate has proven difficult.

0.4.3 The tropics and the southern hemisphere

In the Atlantic sector, ice cores from Andean glaciers in Bolivia and Peru, both south of the Equator, show evidence of the Younger Dryas abrupt climate change (Thompson et al. 1998). On Sajama, in Bolivia, the abrupt shifts at the Bolling/Allerod transition and then into the Younger Dryas were as large as the shift between the depths of the LGM and the current climate. Younger Dryas era glacial advances have also been reported in the Andes but dating is uncertain. These results probably indicate that the cooling encompassed not just the northern hemisphere but also the tropics.

Further afield, abrupt climate changes throughout the last glacial cycle, and including the Younger Dryas, appear in speleotherms from China (Yuan et al. 2004). Two speleotherms, from caves 1000km distant, record remarkably similar changes of $\delta^{18}O$ within them. According to the authors, the isotope content here does not reflect temperature changes but is indicating reduced precipitation during times when Greenland, and much of the northern hemisphere, was cold.

The China monsoon record is consistent with that derived from ocean sediments in the Arabian Sea which records changes in biological productivity, with higher productivity presumed to be caused by stronger monsoons and upwelling. Schulz et al. (1998) found that over the last 65,000 years there was an impressive correlation, independently dated in each record, of weaker monsoons going along with cold in Greenland (see also Altabet et al. 2002). Taken with the China record, this suggests that cold stadials in the northern hemisphere were associated with a weaker monsoon across all of Asia. The changes in monsoon strength are as large as the differences between glacial and interglacial climates. Thus abrupt climate changes were as strong here as around the North Atlantic.

The monsoon records and those from the Cariaco basin, Bermuda rise records and Santa Barbara basin make clear that abrupt climate changes with impacts across the Northern hemisphere and global tropics occurred during the last deglaciation and throughout the last glacial. The Younger Dryas is just the best documented of these events.

Further south the trail runs dry. A report of a Younger Dryas glacial advance in New Zealand (Denton and Hendy 1994) has recently been claimed to be older by several hundred years (Broecker 2003). Both here and in the southern Andes much work remains to be done to identify and date late glacial advances. For the moment, it is clear that abrupt climate changes encompassed the mid and high latitudes in the Atlantic sector, the tropical Atlantic and the Asian monsoon.

0.4.4 The global mean climate

It is not yet clear whether the planet as a whole warmed and cooled during abrupt climate changes. If it did not then it makes sense to look for causes purely in changes in atmosphere and ocean circulations and heat transports. However, if the global mean temperature also changed then the circulation must have interacted with water vapor and/or clouds such that changes in greenhouse trapping and/or albedo allowed the planet to equilibrate with the incoming solar radiation at a different temperature. Changes in sea ice can also change the global mean temperature but have a lesser impact on planetary albedo than clouds because sea ice is most prevalent in locations and seasons with little solar radiation to reflect. Only improved temperature reconstructions from the tropics and southern mid-latitudes during times of abrupt changes will allow us to know if these were associated with planetary warming and cooling.

0.5 ABRUPT CLIMATE CHANGE AND THE DEEP OCEAN CIRCULATION

Even before there was a reliable means of determining past changes in ocean circulation, Broecker et al. (1985) presented the still-reigning paradigm of abrupt climate change: switches on and off of deep water formation in the North Atlantic Ocean and associated changes in the so-called thermohaline circulation (THC). When deep water formation does not occur the subpolar branch of the THC does not operate and surface currents do not bring warm, salty waters northward into the Nordic Seas, there to lose heat to the atmosphere. Consequently the climate around the North Atlantic cools.

The most compelling evidence to date of THC changes during abrupt climate changes is that of McManus et al. (2004) who showed that the THC was very weak between the LGM and the Bolling-Allerod warm transition when it abruptly 'turned on'. It then reduced again to half strength, quite sharply, during the Younger Dryas and then gradually returned to Holocene strength (Figure 3).

As the THC weakens and strengthens the transport of salty water from the subtropical Atlantic to the subpolar Atlantic would be expected to reduce and increase. Consequently during times of a weak THC, the salinity of the subtropical North Atlantic ould be expected to increase. Recently Schmidt et al. (2004) reported there was indeed an inverse relationship between Caribbean Sea salinity and the THC that reinforces the evidence for THC changes. Together with earlier data (Hughen et al. 2000, Bond et al. 1997), these data indicate that abrupt climate changes *can* involve not just surface climate but also the deep ocean circulation or THC. It also indicates that the THC is capable of rapidly 'turning on' and that it can rapidly reduce in strength.

0.6 SEASONALITY OF ABRUPT CLIMATE CHANGE AROUND THE NORTH ATLANTIC OCEAN

Atkinson et al. (1987), using a method based on the current climate tolerances of hundreds of species of carinvorous beetles and the distribution of fossil remains of those species, concluded that over the British Isles the rapid warming of the Bolling-Allerod and the rapid changes of the Younger Dryas involved only modest summer temperature changes but enormous changes in winter temperature. The implied changes in seasonality were enough to convert the British Isles from a climate after the LGM (and after deglaciation of the Isles) similar to that of current day northeastern Russia to one during the Bolling that was similar to that of today, then back again to one of great seasonality during the Younger Dryas and then, finally, back to a modern day climate. Each transition was accomplished in decades.

Denton et al. (2005) also show that around Greenland the Younger Dryas glacier advance is sufficiently limited that it can only be con-

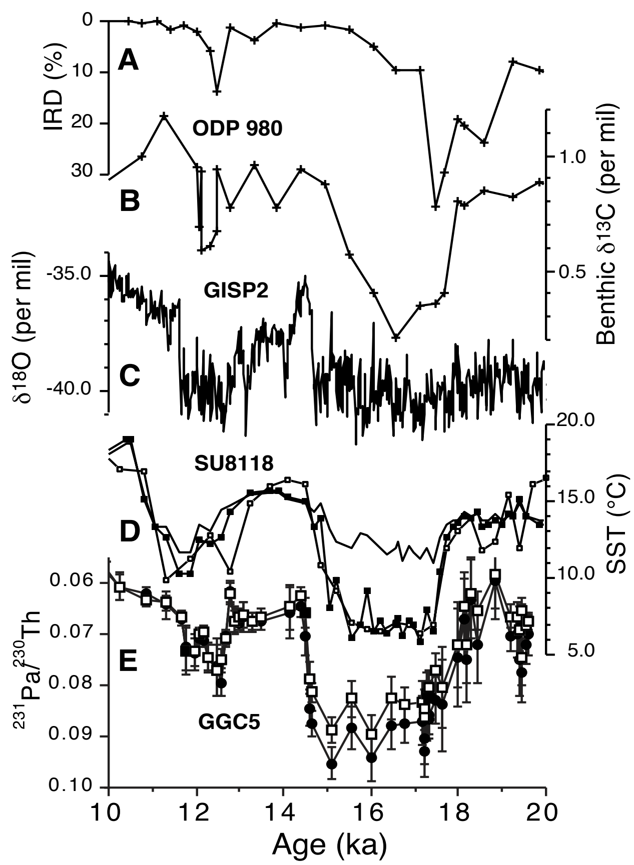

Figure 3 Records of ocean circulation and climate in the North Atlantic region during the last deglaciation from 20,000 to 10,000 years ago. (a) shows ice rafted debris from sediments in the subpolar North Atlantic, (b) shows the benthic $\delta^{13}C$, which is impacted by the strength of deep water formation, (c) shows the GISP2 $\delta^{18}O$ record, (d) shows reconstructed subpolar SSTs from a variety of sources and (e) shows the ratio $^{231}Pa/^{230}Th$ from the Bermuda Rise, a measure of the strength of meridonal overturning. The ratio $^{231}Pa/^{230}Th$ reaches 0.093 for a total cessation of the THC. Figure taken from McManus et al. (2004).

sistent with modest summer cooling. If the annual mean temperature reconstruction from ice cores are correct then this means that winter cooling must have been around $20°C$, comparable with that in the British Isles. As they point out, all the paleoclimate data from around the North Atlantic Ocean, including Norway (Dahl and Nesje 1992), indicates that Younger Dryas cooling was largely contained within the winter while summers cooled more modestly.

Consequently the climate flip-flops measured in the ice cores - and which do seem representative of the climate of the region - represent rapid transitions between two climate regimes. One is a maritime climate akin to the modern one and the other is a climate of marked seasonality in which winters are not tempered by the ameliorating effects of release of heat from the ocean or via atmospheric heat flux convergence. The most common explanation for how winters around the North Atlantic could become so severe is that sea ice expanded southward to the latitude of southern Britain. If winters around the North Atlantic got as cold as the reconstructions suggest they did during stadials and the Younger Dryas then sea ice would almost certainly encroach this far. How this could ever happen is a subject we will shortly turn to.

0.7 THE LACK OF MODERN ANALOGUES OF PAST ABRUPT CLIMATE CHANGES

The period of widespread instrumental observations of weather and climate, basically from the middle Nineteenth Century, when measurements from ships were begun, until the present, contains many climate changes but none that appear to be analogues, even in weakened form, of past abrupt climate changes. The North Atlantic region has experienced climate changes on decadal timescales. These have primarily been associated with changes in the atmosphere circulation. For example the trend from a low index to a high index state of the Northern Annular Mode (NAM) between the 1960s and late 1990s brought striking changes of climate to western Europe including drought in Spain and milder, snowier winters, and advancing glaciers in western Norway. The NAM trended in the opposite direction from the 1920s through to the 1960s. The more recent upward trend has been explained as a consequence of rising greenhouse gases (Shindell et al. 1999) or as a response to Indian Ocean warming (Hoerling et al. 2004). Both explanations make the earlier opposite trend hard to explain. Although basin-wide SST anomalies, that could be related to THC variations, do appear in the North Atlantic they do not seem to explain the NAM behavior. The NAM behavior has been gradual, free of abrupt shifts.

The most celebrated climate shift in the instrumental record is that of 1976/77. This winter ushered in an extended period in which the tropical Pacific Ocean was warmer than normal, as were the waters along the west coast of the Americas while the central North Pacific Ocean was cold (Zhang et al. 1997, Mantua et al. 1997). In the record of tropical tropospheric temperatures the transition does appear quite abrupt (Seager et al. 2004). More generally it appears as the dividing point between a period of strong ENSO events that began with the 1976/77 winter and a period of weaker ENSO activity in the decades before. This climate shift, and perhaps an opposite shift after the 1997/98 El Niño, does testify to the ability of the tropics to organize mid-latitude climate on multidecadal timescales (Hoerling et al. 20004, Huang et al. 2005), but falls short of being directly relevant to past climate changes.

The only other striking climate transition that has occurred in the instrumental record is the shift to a drier climate in the Sahel region of West Africa in the early and mid 1970s. This appears to be related to changes in tropical SSTs, including those in the Indian Ocean (Giannini et al. 2003), although the mechanisms remain obscure. Other monsoons have not gone through such clear transitions. The Sahel drying could be relevant to abrupt transitions into and out off the African Humid Period of the mid Holocene, a time when the region of the current Sahara Desert was grassland (deMenocal et al. 2000).

Neither indices of tropical climate variability (e.g. NINO3) nor extratropical circulation variability show evidence of bimodality such as that seen in the Greenland ice core data (Wunsch 2003) and efforts to locate regime-like behavior in the climate system have so far failed (Stephenson et al. 2004). Since regime-like behavior did occur in climates of the past, this emphasizes that past abrupt climate changes are different, not just quantitatively, but also qualitatively, from those in the instrumental record.

0.8 EXAMINING PROPOSED CAUSES OF ABRUPT CLIMATE CHANGE

Next we turn our attention to the possible causes of abrupt climate change. First we will summarize what needs to be explained.

0.8.1 The spatial character of abrupt climate changes

According to the studies described in the previous sections, the climate of the North Atlantic region, during glacial times, moved between two different states of operation. The transitions in between occurred rapidly, especially for the warming. These rapid climate changes involved striking temperature changes across western Europe and eastern North America, enormous in winter but modest in summer. Consequently there were abrupt changes in the degree of seasonality.

During North Atlantic cold stadials surface ocean temperatures in the subtropical North Atlantic cooled, the ITCZ over South America shifted south, the tropical Americas cooled and the Asian monsoon weakened. In the tropical regions the transitions were as large as the difference between full LGM and modern states. Hence, the abrupt climate change signal does not appear to become more muted with distance from the North Atlantic. Any proposed mechanism must be able to explain these observed climate changes.

0.8.2 Strengths and weaknesses of the THC-driving theory

0.8.2.1 Role of the THC in today's climate

Because of the North Atlantic branch of the THC, with deep sinking at high latitudes compensated by northward flow at the surface and southward flow at depth, the North Atlantic Ocean moves heat northward at all latitudes. The following discussion is based on Seager et al. (2002). The North Atlantic Ocean moves about 0.8PW across $35°N$ (Trenberth and Caron 2001), enough to warm the area north of $35°N$ by $3-4°C$. This pales in comparison to a warming of $27°C$ due to the vastly greater atmosphere heat transport across $35°N$ and a warming of another $27°C$ in winter due to seasonal release of heat stored since the last winter. Not all of this ocean heat transport (OHT) is due to the THC as the subtropical and subpolar gyres and wind-driven overturning also contribute. Those circulations persist even when the THC is weakened or shuts down leaving a poleward OHT, though one that is greatly reduced.

The heat transported by the North Atlantic Ocean is released to the atmosphere primarily in two regions. The first is in the Gulf Stream region east of North America where, during winter, cold, dry air from the continent flows over the warm waters offshore extracting up to $400Wm^{-2}$, in the seasonal mean, from the ocean. A sizeable portion of this heat is picked up by transient eddies - atmosphere storms -

and converged over eastern North America ameliorating winters there. The transient eddy heat flux, as always, is acting diffusively to oppose the temperature contrasts created by stationary waves and the seasonal release of heat by the ocean (Lau 1979). The other region where the North Atlantic OHT is preferentially released is in the Norweigian Sea keeping it ice free in winter and warming the coast of Norway. Because of this geography of heat release the North Atlantic OHT warms the climate on both sides of the ocean leaving the contrast of about $15°C$ to be explained by the more basic continental-maritime climate distinction and by stationary waves, especially those forced by flow over the Rocky Mountains.

0.8.2.2 The spatial pattern of THC-induced climate change

Many modeling groups have performed experiments in which the THC in a coupled ocean-atmosphere GCM is forced to shut down, usually by addition of a massive amount of freshwater to the surface of the subpolar North Atlantic Ocean (e.g. Manabe and Stouffer (1997), Rind et al. (2001),Vellinga et al. (2002), Vellinga and Wood (2002), Zhang and Delworth (2005)). Freshwater dumping is usually justified in the paleoclimate context as an idealized representation of a meltwater discharge from glacial dammed lakes[2] . All these experiments agree that once the water columns of the subpolar North Atlantic have been stabilized by the addition of low density fresh water, deep water formation is reduced or ceases, poleward flow into the region is weakened, the heat transport reduces and the sea ice extent increases. They also all agree that the North Atlantic region cools by as much as several degrees Celsius in the region of Iceland and that the cooling extends into Europe and over Greenland although at reduced strength.

The annual mean cooling over Greenland induced by a THC shutdown is only about $3°C$ (Manabe and Stouffer 1997) or less (Zhang and Delworth (2005), Figure 4)), many times smaller than that observed for abrupt climate changes (Severinghaus and Brook 1999). The modeled cooling over western Europe is also at most a few degrees Celsius, much less than that reconstructed from beetles (Atkin-

[2]The sudden discharge of ice from continental ice sheets directly into the ocean is another source of freshwater. These are called Heinrich events and can be traced in ocean sediments by the debris carried within the ice. It has been suggested that they occur at the end of a cooling cycle (Clarke et al. 1999) but in general it is not well understood how they fit into climate changes and they are not dealt with here. See review by Hemming et al. (2004).

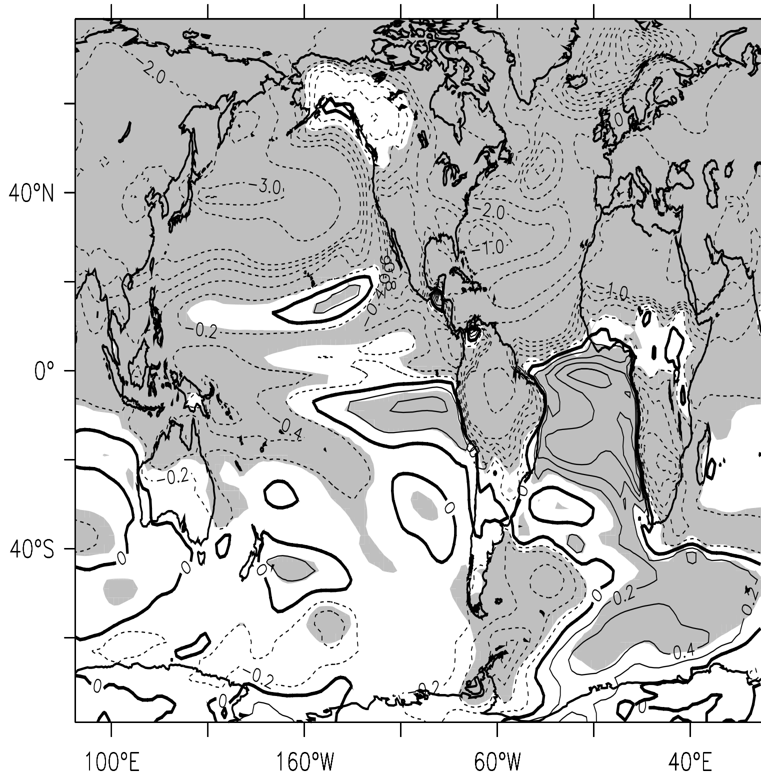

Figure 4 The change in annual mean surface air temperature between two states of a coupled GCM, one with a collapsed thermohaline circulation and one with an active thermohaline circulation. The model was the latest version of the GFDL coupled GCM. Shading indicates the change is significant at the 95% level. The figure is taken from Zhang and Delworth (2003).

son et al. 1987) or periglacial evidence (see Denton et al. (2005)). All models agree that the North Atlantic cooling extends down into the subtropics and perhaps as far as the Equator, but that south of $45°N$ the cooling is only of the order of $1°C$, less than that reproduced by Sachs and Lehmann (1999). The models also do not produce a strong tropical cooling over South America, in conflict with ice core records there for the Younger Dryas (Thompson et al. 1998).

Rind et al. (2001), Vellinga and Wood (2002) and Zhang and Delworth (2005), using different coupled GCMs, all show that for a THC shutdown the ITCZ moves south in the tropical Atlantic, broadly consistent with cooling of the North Atlantic Ocean that occurred in the models, and interpretation of the Cariaco Basin record in terms of a reduction in precipitation over northern South America. The precipitation changes are modest. The models of Vellinga and Wood (2002) and Zhang and Delworth (2005, see figure 5) have modest reduction of precipitation in the Asian monsoon region while the Rind et al.

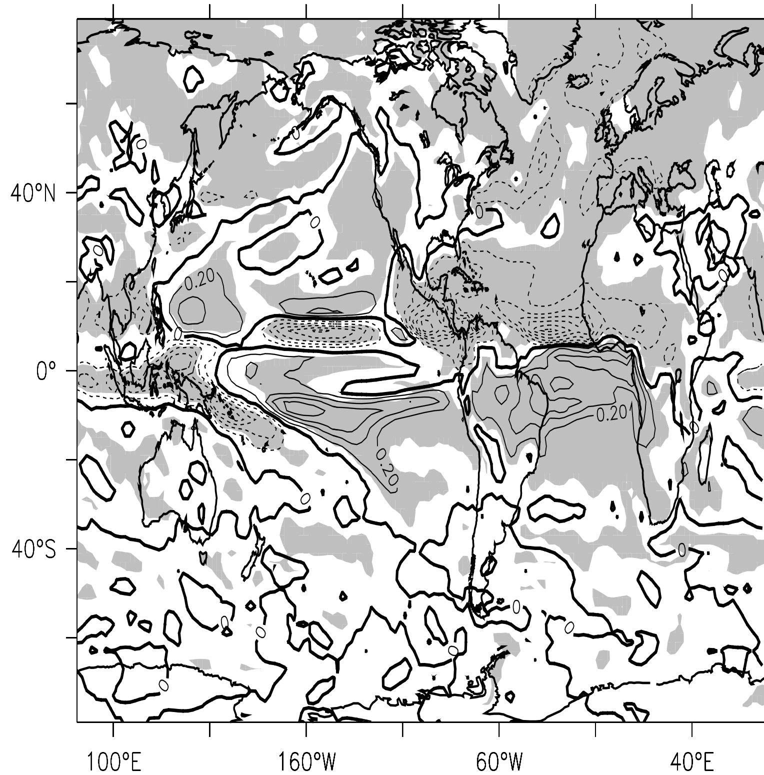

Figure 5 The change in annual mean precipitation (m/year) between two states of a coupled GCM, one with a collapsed thermohaline circulation and one with an active thermohaline circulation. The model was the latest version of the GFDL coupled GCM. Shading indicates the change is significant at the 95% level. The figure is taken from Zhang and Delworth (2003).

(2001) model has a very modest weakening of the Indian monsoon and an equally modest strengthening of the East Asian monsoon.

In the North Atlantic region, therefore, there is sufficient agreement between models and paleoclimate data that changes in the THC must have been involved in abrupt climate changes. THC slowdowns or shutdowns caused cooling around the North Atlantic and a southward shift of the tropical Atlantic ITCZ and THC resumptions caused regional warming and moved the Atlantic ITCZ back north. This said, changes in the THC, even shutdowns - at least as represented in GCMs - cannot explain the magnitude of the cooling around the North Atlantic, despite large increases in sea ice cover in the surrounding seas (Manabe and Stouffer 1997, Rind et al. 2001), or in the subtropics (Sachs and Lehmann 1999). Therefore, even on its own home turf, the THC theory falls short of being able to offer a complete explanation of abrupt climate changes, unless all existing coupled GCMs are significantly in error.

Outside of the North Atlantic region, the THC theory of abrupt climate change cannot entirely explain the paleoclimate data. According to GCMs, the impact of the THC on temperature and precipitation over equatorial and southern South America is too weak to explain the impressive documentation of the Younger Dryas in tropical ice cores. Changes in the THC also cannot explain the equally impressive reduction in monsoon strength, coherent across the Asian monsoon, that occurs during cold stadial events when the THC was weaker.

0.8.2.3 The temporal behavior of the THC

McManus et al. (2004) showed, using radiochemical data, that the North Atlantic THC was operating during the LGM but in a 'drop dead' state during the beginning of the last deglaciation between the LGM and about 14.7 kyr ago. Then it abruptly increased to near modern strength, apparently in decades, coinciding with the dramatic Bolling-Allerod warming. At the beginning of the Younger Dryas the THC rapidly weakened, but remained active, and at the end it more gradually recovered to Holocene values. This remarkable result confirmed what had been suggested for a while, the THC is not a sluggish part of the climate system but can shift between modes of operation in years to decades. What can cause such changes?

Manabe and Stouffer (1988) showed that a coupled GCM (the GFDL one) had two stable modes of operation, one with an active North Atlantic THC and one with a 'drop dead' THC that could be induced by a massive addition of freshwater into the subpolar North Atlantic Ocean. This work inspired a generation of similar experiments and led to the development of the dominant paradigm of abrupt climate change: releases of glacial meltwater, whether it be from ice-dammed lakes or ice surges, caps the North Atlantic Ocean with fresh surface water shutting down deep water formation and turning off the flow of warm water from the subtropical North Atlantic into the subpolar Atlantic, thus cooling regional climate which is amplified by an increase in sea ice extent.

Rind et al. (2001), using a coupled GCM with a free-surface ocean model that allows for an increase in river flow at any chosen location to be directly specified, were able to induce a North Atlantic THC shutdown within a decade or two when the flow through the St. Lawrence was increased. However to do this required an inflow of 20Sv for five years. Licciardi et al. (1999) and Clark et al. (2001) have attempted to reconstruct the history of freshwater flux from North America into the Atlantic Ocean during the last deglaciation. They show jumps of a fraction of a Sverdrup in combined St. Lawrence and Hudson River runoff occurring as a result of reroutings of continental drainage and from sudden emptying of ice-dammed lakes (such as Lake Agassiz). For changes in freshwater flux to the North Atlantic of this magnitude, coupled GCMs agree that the THC would weaken by only a modest amount and only very gradually, say, over hundreds of years (Manabe and Stouffer 1997, Rind et al. 2001).

If the coupled GCMs are correct, then realistic freshwater influxes cannot explain the rapid decreases in the North Atlantic THC that, almost certainly, seem to have occurred in the past. Further, the paleoclimate record shows that in the North Atlantic region, it was actually the *warmings*, and THC resumptions, rather than the *coolings*, and THC slowdowns or shutdowns, that were the most abrupt. Coupled GCMs can produce rapid cessations of deep water formation if given apparently unrealistic perturbations but none has yet produced an abrupt resumption of deep water formation and the THC. Instead, after a period of a weak or nonexistent THC, the THC gradually returns over a hundreds years or so (Vellinga et al. 2002). It is also not clear that all of the abrupt changes seen in Figure 1 were the result of freshwater perturbations. In fact that seems rather unlikely suggesting other mechanisms whereby the THC can be turned on and off.

Simple climate models (often called 'intermediate' models) that contain more than one stable mode of operation of the THC can reproduce many aspects of observed climate records including rapid THC resumptions and warmings (Ganopolski and Rahmstorff 2001). The finding of multiple equilibrium states in the GFDL coupled model lent credibility to such models. However, the key physics acting in the intermediate climate models that have produced regime like behavior in the THC include ocean convection, advection and diffusion. The realism with which these processes are represented is effected by the very coarse horizonal and vertical resolution within the intermediate models. Intermediate models have non-trivial problems in simulating the affects of topography on circulation which influence where convection can take place and its stability of location and strength. Similarly, the atmospheric components of the intermediate models are, essentially, extended energy balance models. It is not clear that regime-like behavior would occur if the same ocean models were coupled to more realistic atmospheric models (such as those that allow for weather).

In general, it needs to be demonstrated that multiple regimes can be supported by models with higher resolution that adequately resolve the physics responsible for the multiple regimes in intermediate models. However to date, it is not even clear whether coupled GCMs other than the Manabe and Stouffer GFDL model have multiple equilbrium states. Vellinga et al. (2002) say they have not found this behavior in the Hadley Centre coupled GCM. In general the GCM model results are at sufficient variance with the paleoclimate record to raise several questions that will be addressed shortly.

0.8.3 Summary

There is no doubt that abrupt climate changes, such as the stadial-interstadial transitions of the last ice age and the Bolling Allerod warming and Younger Dryas of the last deglaciation, involve changes in the North Atlantic THC as an active component. However changes in the THC alone cannot explain the known global climate changes associated with these events, especially in the tropics, even accounting for its impacts on sea ice. Further, no state-of-the-art climate model has shown that regime-like behavior of the THC, with rapid transitions between states, is possible. On this basis we suggest that there is a lot more to the puzzle of abrupt climate change than changes of the THC.

0.9 ATMOSPHERIC CIRCULATION REGIMES AND GLOBAL ATMOSPHERE-OCEAN COUPLING AS POSSIBLE CAUSES OF ABRUPT CLIMATE CHANGE

The discussions of the spatial extent of abrupt climate changes in glacial times and during the last deglaciation should make it clear that the causes must be found in changes in the general circulations of the *global*, as opposed to *regional*, atmosphere and ocean circulation. The idea that the THC changes, directly impacting a small area of the globe, and that, somehow, most of the rest of the world piggy-backs along in a rather systematic and reliable way seems decidedly dubious.

0.9.1 The problem of North Atlantic climate change

Consider the seasonality changes around the North Atlantic Ocean going from the LGM through the Bolling-Allerod abrupt warm transition and then cooling into the Younger Dryas followed by the second abrupt warm transition that ended it. A wide collection of evidence indicates that winter climate in, for example, the British Isles changed up and down by about $20-30°C$ during these transitions and summer temperatures by $4-6°C$ (e.g. Atkinson et al. (1987)).

This could be accomplished if the sea ice edge extended south of the British Isles during winter and then retreated far north in summer. Imposing this seasonal cycle of sea ice cover under an atmosphere GCM, Renssen et al. (2001) reproduced, approximately, the observed different deglacial climates in a set of time snapshot experiments. When sea ice extends that far south, and if it is thick enough with no gaps, the surface temperature of the ice and the air above drops dramatically in winter as the atmosphere becomes insulated from the ocean below. It is the sea ice extension, rather than the presence of ice sheets (which existed throughout the Bolling-Allerod and Younger Dryas over North America and Scandinavia), that causes winter cooling in the North Atlantic sector. Ice sheets in winter are no more of a radiative sink than a cold, snowy land surface.

But sea ice never extends this far south in coupled GCMs when the THC is forced to shutdown. This is consistent with the fact that in the North Pacific and Southern Ocean sea ice typically does not extend equatorward of 60° even though, unlike the current North Atlantic Ocean but similar to one with a THC shutdown, there is close to zero poleward ocean heat transport there. Sea ice is melted from below and so can depend on the ocean heat transport but the placement of the ocean heat transport depends on the wind stress. In THC shutdown experiments the sea ice expansion is restricted by the atmospheric circulation.

Assuming that, by some means, sea ice did extend as far south as the British Isles during the winters of stadials, the relative summer warmth then requires it to retreat far to the north and for the ocean to warm up tremendously. As a point of comparison, in the current climate ocean areas that are ice covered at the end of winter do not achieve temperatures of more than about $2°C$ in summer.

Thus the problems posed by abrupt change in the North Atlantic region are:

1. How could sea ice extend so far south in winter during the stadials?

2. How, during the spring and summer of stadials can there be such an enormous influx of heat as to melt the ice and warm the water below by close to $10°C$? If 50m of water needs to be warmed up by this much in four months it would take an average net surface heat flux of $150Wm^{-2}$, more than twice the current

average between early spring and mid summer and more than can be accounted for by any increase in summer solar irradiance (as during the Younger Dryas).

3. How can this stadial state of drastic seasonality abruptly shift into one similar to that of today with a highly maritime climate in western Europe? Remember that both states can exist in the presence of large ice sheets over North America and Scandinavia.

0.9.2 Required changes of atmospheric circulation regimes and heat transports

To solve the first two problems we must imagine a stadial climate in which the heat transport has almost the opposite seasonal cycle to that of today. Whereas now winter atmospheric and ocean heat transport holds back the sea ice in the North Atlantic, during stadials weak heat transport in the mid to high latitudes must have allowed the sea ice to advance south. In contrast, during the summers of stadials, there must have been strong transport to melt back the sea ice and establish mild summers.

In thinking of ways to reduce the winter convergence of heat into the mid and high latitude North Atlantic, we might begin with the storm tracks and mean atmosphere circulation. The Atlantic storm track and jet stream have a clear southwest to northeast trajectory whereas the Pacific ones are more zonal over most of their longitudinal reach (Hoskins and Valdes 1990). If the Atlantic storm track and jet could be induced to take a more zonal track, akin to its Pacific cousin, the North Atlantic would cool.

The cooling over western Europe and the North Atlantic Ocean would be driven by less southerly flow and advective warming in the winter stationary waves - the real reason for the mildness of west European winters (Seager et al. 2002). Transient eddy heat transports, which act diffusively on temperature, would oppose the cooling as the storm track relocated towards the Mediterranean.

0.9.3 Impacts of an hypothesized shift to zonal circulation during winter in the North Atlantic sector

An essentially zonal wind flow across the North Atlantic Ocean could set in motion a chain of events that establish a cold North Atlantic climate. First of all the removal of warm southwesterly advection into the North Atlantic will directly cool the ocean and coastal regions there. In the current climate the flow of water in the North Atlantic

Drift from the Gulf Stream and into the Nordic Seas is controlled by the wind stress pattern and reflects the northward tilt of the Atlantic jet stream and storm track. This water is salty and, as it cools on its northward track, becomes dense enough to sink to the bottom. The northward flow of water was the ultimate explanation of Warren (1983) for why deep water is formed in the North Atlantic and not the North Pacific (see also Emile-Geay et al. (2002)). If the wind stress pattern becomes zonal the North Atlantic Drift will flow directly across the Atlantic towards France and Spain instead of towards the Nordic Seas, reducing the salt flux into the subpolar Atlantic and causing the THC to shutdown and reduce ocean heat flux convergence in the Nordic Sea.

In the current climate the sea ice edge is very much controlled by the pattern of the winds through the influence they have on both the ice drift and the atmosphere heat transport. For example positive phases of the NAO go along with less ice in the Greenland and Barents Seas, where the anomalous winds are from the south, and more ice in the Labrador Sea where the anomalous winds are from the north (Deser et al. 2000). On longer timescales changes in wind will impact the ocean heat transport and this will also influence the sea ice cover. A shift to more zonal winds across the North Atlantic will, by all processes, allow sea ice to extend further south than it currently does, cooling the North Atlantic regional climate.

Currently the northward flow of the Drift helps sustain winter heat release from the ocean, especially north of Scotland. The heat release and diabatic heating of the atmosphere above helps maintain the Icelandic Low. This was shown in the GCM experiments of Seager et al. (2002) and is implicit in the modeling of Hoskins and Valdes (1990). The Low maintains the northward deflection of the storm track, jet and the North Atlantic Drift. Thus the interaction between the atmosphere and ocean circulations over the North Atlantic appears to be self-reinforcing. Perhaps forcing of this system from outside, maybe in the tropics, can set this reinforcing mechanism running in reverse and establish a stable zonal jet and storm track, a zonal North Atlantic Drift, a collapsed THC and a cold North Atlantic.

Although a shift to a zonal circulation across the North Atlantic would cause extensive cooling of the European region on its own it would be assisted by the induced THC shutdown. To date explorations of THC shutdowns have all focused on the impact of freshwater discharges from melting ice sheets or ice damned lakes. To our knowledge the impact on the THC of a sudden shift in the Atlantic to a more Pacific-like wind stress regime has never been investigated.

It would decrease the warm, salty water flow towards the Nordic Seas that, currently, as it cools, becomes dense enough to sink to the abyss. With that inflow shut off by the altered wind stress pattern it at least appears possible that the THC will shutdown too.

0.9.4 Summer climate and abrupt shifts in seasonality

During the Bolling warm period and the period after the Younger Dryas the climate of western Europe had a seasonality similar to that of today but during the cold spells while winters were extremely cold, summer temperatures remained close to $10°C$ (Atkinson et al. 1987, Denton et al. 2005). Not surprisingly such summer temperatures can be reproduced for these periods in an atmosphere GCM when the North Atlantic SSTs are specified to also be that warm (Renssen and Isarin 2001) During the cold periods the SSTs need to warm from freezing to about $10°C$. Currently the only regions of the world ocean that have a seasonal cycle that large are in the western boundary currents east of North America and Asia. Here warm moist advection around the summer subtropical anticyclones warms the SSTs and cold dry advection of the continents, as well as transient eddies, cool the SSTs in winter (Seager et al. 2003a).

The summer warmth and increased seasonality require a much larger heat import into the North Atlantic region by the atmosphere and ocean during summer than currently occurs. One possible cause of this is the presence of extensive ice sheets over North America and Scandinavia. During winters ice sheets do not significantly perturb the surface or planetary radiation budget but in summer they are a vast radiative sink as they reflect solar radiation that otherwise would be absorbed at the surface. This radiative sink, and the associated cold temperatures, will induce an anomalous convergence of atmospheric heat transport over the ice. This could cause a much larger export of heat from the tropics into high latitudes during summer than is currently the case.

Few GCM studies have examined the the impact of ice sheets on seasonal energy transports. Hall et al. (1996) did find greatly increased summer atmosphere heat transport in an LGM simulation, although the fixed SSTs in the study make the results questionable. Summer ice sheets will also impact the stationary waves. During summers poleward warm advection around the Icelandic Low (which, unlike the Aleutian Low, is still present in summer, though weak) helps warm the coast of Scandinavia while further south cold advection around the North Atlantic subtropical high keeps the coasts of

Portugal and North Africa cool (Seager et al. 2003a). If, during the summers of cold periods such as the Younger Dryas, the Icelandic Low was strong and south of its current location then it could cause advective warming of western Europe. It will be well worth examining how the residual Laurentide and Scandinavian ice sheets impacted the summer stationary wave climate, via their orography and albedo, and how this impacted summer temperatures and seasonality.

0.9.5 Stratosphere-troposphere coupling and abrupt climate change

Recent years have seen a surge of research on how changes in stratosphere circulation can cause changes in tropospheric circulation and potentially explain observed trends in the northern and southern annular modes (see Hartmann et al. (2000)). Kushner and Polvani (2004) demonstrated in a simple, dry GCM that changes in the stratospheric radiative equilibrium temperature could cause changes in the tropospheric circulation extending down to the surface. As the stratosphere was cooled the tropospheric jet moved from being a subtropical feature isolated from the polar night jet to becoming a mid-latitude jet contiguous with the stratospheric jet. This results from a two way coupling between the stratosphere and the troposphere mediated by transient eddies. There is some hint that the shift between jet regimes does not occur smoothly.

It is hard to assess the significance of this result for abrupt climate change (not least because of the idealized model which, for example, lacks stationary waves) but changes in the stratospheric winter jet will inevitably occur in response to changes in trace gas composition and orbital configuration and these will impact the tropospheric circulation. Although it is unlikely that the stratospheric influences on the troposphere are of sufficient size to uniquely explain past changes in tropospheric circulation, stratosphere-troposphere coupling could be part of the mix of processes that combine to create thresholds in circulation regimes.

0.9.6 The tropical circulation and abrupt climate change

0.9.6.1 Tropical forcing of global climate variations

There are many reasons to think that the tropics play an active role, and maybe an organizing one, in abrupt climate change and are not a backwater responding passively to climate changes organized by the North Atlantic Ocean. For one thing the paleoclimate record shows that abrupt climate changes are, relatively, as large in the tropics (e.g. the Asian monsoon and Andean ice cores) as in the North Atlantic region (Denton et al. 2005). While models do show that weakening and strengthening of the Atlantic THC can inspire significant tropical climate change (Zhang and Delworth 2005, Vellinga and Wood 2002), the changes seem to fall well short of those that actually did occur. It is equally plausible that past abrupt changes occurred as part of a global climate reorganization instigated within the tropics.

The other reason for looking to the tropics is that in the current climate many climate changes around the globe throughout the twentieth century have been forced from the tropics through varying SSTs and patterns of tropical convection. This definitely includes the major droughts and pluvials over the Americas (Schubert et al. 2004, Seager et al. 2005, Huang et al. 2005), the drying of the Sahel (Giannini et al. 2004) and, quite possibly, the trends in the Northern Annular Mode (Hurrell et al 2004, Hoerling et al. 2004, Schneider et al. 2003). The tropical Pacific may also be able to exert a control on the Atlantic THC (Latif et al. 2000) through its influence on rainfall over the tropical Americas and the Atlantic Ocean and the vapor flux across Central America.

0.9.6.2 Limitations of the ENSO blueprint

Although all this is true, so far it has not been demonstrated that the tropics in any way control abrupt climate changes. The dominant mode of year to year and decade to decade climate variability in the tropics relates to the El Niño-Southern Oscillation (ENSO). Numerous attempts to explain past tropical SST changes have invoked changes with an ENSO-like spatial pattern (e.g. Koutavos et al. (2002)) and the global impacts of ENSO have been appealed to as a cause of climate change on glacial timescales (Cane 1998). Certainly ENSO responds to orbital and other external forcing and may even respond abruptly to gradual forcing (Clement et al. 1999, 2000, 2001, Mann et al. 2005).

Clement et al. (2001) suggested that the peculiar orbital forcing of the Younger Dryas interval stabilized the tropical Pacific atmosphere-ocean system resulting in long periods without interannual variability and a persistent change in the mean state with a La Niña-like pattern. While this result is compelling the global climate changes during the Younger Dryas do not fit the typical La Niña pattern. Tropical cooling, as implied by Andean ice core records for the Younger Dryas, is consistent with a La Niña-like state but the weak Asian monsoon during stadials is more typical of an El Niño like state (Krishna Kumar et al. 1999). La Niña events also warm the mid-latitudes of each hemisphere (Seager et al. 2003b) whereas they clearly cooled during the Younger Dryas and glacial stadials.

It is true that the climate response associated with persistent El Niño-like, or La Niña-like anomalies need not be the same as the one that goes along with interannual variability. However experiments with coupled models in which persistent El Niño or La Niña states were induced (Hazeleger et al. 2005 and unpublished results conducted by the first author with the GISS and CCM3 climate models) produced a response akin to the interannual one: during persistent El Niños the tropics warm, the mid-latitudes cool and the poles warm and there is a rather small global mean temperature change (Seager et al. 2003b). At least in these experiments persistent changes in ENSO did not excite positive feedbacks involving water vapor or clouds that significantly amplified climate change.

The spatial pattern of abrupt change does not fit the ENSO blueprint indicating that in pursuing tropical involvement in abrupt climate change we need to think beyond ENSO. This need is highlighted by two problems of the model studies mentioned above. First, in interannual variability an El Niño warming of the eastern tropical Pacific is caused by a transient adjustment of the ocean circulation and upper ocean heat content. On longer timescales relevent to different climate regimes the changes in ocean circulation and heat transport must be in equilibrium with the atmospheric circulation. In this equilibrated case changes in SST must be sustained by different processes than for interannual changes in SST (Hazeleger et al. 2004). They will probably have different spatial patterns and different climate consequences.

Second, the models that were used to examine the global response to persistent El Niños and La Niñas (Hazeleger et al. 2005) did not allow for ocean circulation adjustment. It is an open question how persistent tropical climate changes impact the global ocean circulation, thermocline structure and heat transports. In both cases the challenge is to think of the full range of possible tropical and global atmosphere-ocean coupling and to think outside of 'the ENSO box'.

0.9.6.3 Tropical heating and extratropical jets and storm tracks

Clearly, tropical climate changes have the *potential* to cause significant extratropical climate change. In an intriguing paper Lee and Kim (2003) have argued that the Northern Hemisphere contains two dynamically distinct jet streams. One is an 'angular momentum con-

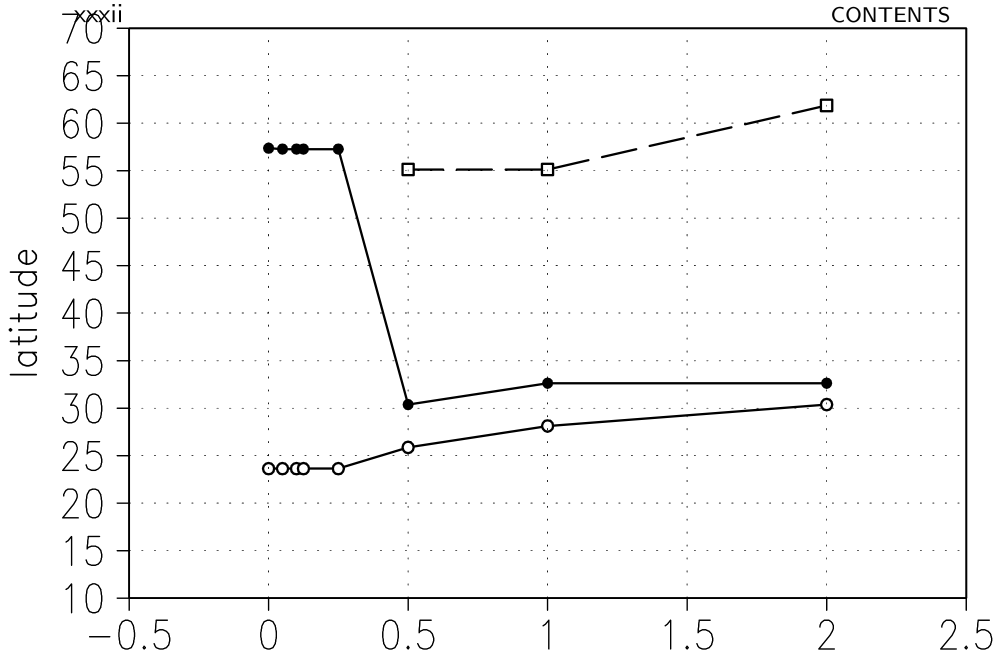

Figure 6 Latitudes of the subtropical jet (line with open dots), the primary (line with closed dots) and secondary (dashed line with open squares) eddy-driven jets as a function of the strength of an imposed tropical heating (horizontal axis). Results were generated from simulations with simplified models with the eddy-driven jet latitudes predicted with the unstable normal modes of an axisymmetric flow. Figure taken from Lee and Kim (2003).

serving' subtropical jet on the poleward flank of the Hadley Cell and the other is an 'eddy-driven' jet further poleward. The Asian sector has only a subtropical jet. Over the Atlantic sector, during winter, both jets exist with a subtropical jet that begins west of Africa and extends across Africa and Asia and an eddy-driven jet that begins over the southern United States and extends up to the British Isles and Scandinavia. This picture is broadly consistent with the observations of Palmen and Newton (1969).

Lee and Kim argue that the subtropical and eddy-driven jets compete for the attention of transient eddies. When the subtropical jet is strong enough, the meridional temperature gradient with which it must coexist, is potent enough to organize transient eddy activity resulting in a relatively southern storm track, as over the Pacific Ocean. Where the subtropical jet is weaker the self-reinforcing interaction between eddies that feed off temperature gradients, the momentum fluxes off those eddies that drive jets - and associated temperature gradients - allows the establishment of a relatively northern jet, as over the Atlantic Ocean.

Lee and Kim show that the competition between the two jets is modulated by the strength of the tropical heating (Figure 6). When this is strong enough the subtropical jet is strong enough to 'capture' the transient eddies and merge the subtropical and eddy-driven jets. Their results are based on a collection of idealized and theoretical calculations but suggest that there is some distribution of tropical heating that would cause the eddy-driven Atlantic jet to be captured by the subtropical jet west of Africa. Were this to occur the Atlantic storm track would become reoriented to trend directly east from the Southern United States. This would move southward the latitude of poleward heat transport over the Atlantic potentially drastically cooling the North Atlantic region and also potentially impacting the sea ice distribution and the Atlantic THC via the changes in surface wind stress.

According to Yin (2003) southward movement of tropical convection during northern winter strengthens the northern hemisphere subtropical jet, which is consistent with the results of Lindzen and Hou (1988). A southward shift of the ITCZ in the longitudes of the Americas could lead to the Atlantic subtropical jet 'capturing' the transient eddies. This would cause a weakening of the eddy-driven jet over the North Atlantic, analogous to the mid-winter suppression of the North Pacific storm track (Yin 2003). This would reduce the atmospheric flux of heat into the NE Atlantic sector and, via changes in the surface wind stress and curl, allow the sea ice to shift southward. The change in surface wind stress would also reduce, or eliminate, the flux of warm, salty water from the subtropical North Atlantic into the subpolar Atlantic and thereby reduce, or shutdown, the THC.

These processes would also operate in the classical paradigm for abrupt climate change, which features abrupt shifts in the THC as the causal agent. For example, if there was a sudden resumption of the THC (for whatever reason) and the sea ice moved northward, the subtropical North Atlantic atmosphere and ocean would warm and the ITCZ would shift farther north (Chiang et al, 2003). A shift in the ITCZ northward across the equator would weaken the subtropical jet and cause the storm track in the North Atlantic to strengthen and shift northward into the Nordic Seas. This would reestablish the transport of warm, salty water into the subpolar North Atlantic further encouraging a strong THC.

Hence, interactions involving both the atmosphere and ocean in the North Atlantic-Americas sector could act as an amplifier of climate change linking the high latitudes and the tropics. We have already discussed evidence that the ITCZ over the Atlantic and Americas does move south during Greenland stadials (Peterson et al. 2000, Wang et al. 2004). To date this has been viewed as little more than a response to cooling of the North Atlantic Ocean but it would be immediately fruitful to examine the complete nature of two-way coupling between the ITCZ and the atmosphere and ocean circulation in the mid and high latitude North Atlantic region, both in modern and glacial climates.

0.9.6.4 Near-global atmosphere ocean coupling and tropical climate reorganization

ENSO and decadal ENSO are oscillations of the tropical Pacific atmosphere and ocean. The climatological winds over the tropical Pacific Ocean can quite closely explain the spatial variation of tropical Pacific thermocline depths according to Sverdrup dynamics (Veronis 1973) and, with the inclusions of Ekman dynamics, the creation of a warm pool and a cold tongue (Clement et al. 2005). The same dynamics can explain the transient adjustment of the thermocline to varying winds (Cane 1984). A central element is an adjustment to balance at the Equator between the thermocline (or sea level height) tilt and the zonal wind stress. What this dynamics cannot explain is the mean thermocline depth.

Boccaletti et al. (2004) point out that the mean depth has to be related to the global surface heat budget and ocean heat transport. This is because a shallow equatorial thermocline allows upwelling to expose cold water that acquires a net downward surface heat flux. Wind-driven overturning exports this heat poleward. A deeper thermocline would allow less poleward ocean heat transport. While this is true the details of the adjustment between the thermocline, winds, currents and the ocean and atmosphere heat transports are opaque.

Huang et al. (2000) have pointed out that, by reducing the transfer of mass from the upper layer of the ocean to deeper layers, cessation of North Atlantic Deep Water formation would cause the tropical Pacific thermocline to migrate down. The adjustment occurs by coastal and equatorial Kelvin waves and begins within a decade or two. This should cause a reduction of poleward tropical ocean heat transport. The thermocline depth and structure must also be impacted by surface buoyancy fluxes, water mass transformation and subduction within the extratropics where water that eventually upwells at the Equator leaves the surface. Relatively little work has been done on this beyond theoretical explorations but Hazeleger et al. (2001, 2004) have shown that variations in the mid-latitude storm tracks and circulation can have a significant impact on the tropical Paciific thermocline. It remains to be seen how, for example, plausible shifts in the the storm tracks and jet streams in past climates impacted the tropical oceans.

0.9.6.5 Ocean and atmosphere heat transports and the global climate

If it is really true that global atmosphere-ocean coupling involving changes in storm tracks, the mid-latitude westerlies and the THC can impact the depth and structure of the tropical Pacific thermocline then the potential exists to shift the partitioning between the tropical atmosphere and ocean heat transports. Held (2002) argued that this partitioning cannot change because of the dynamical coupling between the Hadley Cell and the meridional ocean overturning. However, the constraint is not nearly so tight once the tropical oceanic gyre transport, which moves heat equatorward, is considered (Hazeleger et al. 2004, 2005).

It is the total transport by atmosphere and ocean that is most tightly constrained, apparently by the radiation budget at the top of the atmosphere (Clement and Seager 1999). Consequently a reduction of wind-driven tropical ocean heat transport causes a compensating increase in atmosphere heat transport, a universal result with all manner of models in all types of experiments (Manabe et al. 1975, Cohen-Solal and LeTreut 1997, Clement and Seager 1999, Winton 2003). It is plausible that a deeper tropical thermocline, by reducing the poleward ocean heat transport, could cause the atmosphere to carry a larger share of the total transport.

It is also a common model result that as the tropical ocean heat transport is reduced the subtropical SSTs cool and the marine low level cloud cover and planetary albedo increase. In addition, tropical deep convection becomes more confined towards the Equator resulting in reduced atmospheric water vapor and reduced greenhouse trapping in the subtropics. Both effects cool the planet (Clement and Seager 1999, Winton 2003, Herweijer et al. 2005). Thus an ocean adjustment to a deeper equatorial thermocline, as could be induced by a THC shutdown or some unknown change the extratropical atmosphere circulation, would be expected to cause a cooling of the global climate.

0.9.7 Discussion

The global atmosphere-ocean coupling idea of abrupt climate change, with an active or organizing role for the tropics, is pure speculation. To date no one has shown that the tropical-extratopical atmosphere-ocean circulation has different modes of operation with radically different climates but, then again, no one has tried. The tropical equivalent of a North Atlantic 'hosing' experiment capable of causing a model climate to flip into an alternate state has yet to be devised.

There also remains the tricky problem of what causes the climate to remain stuck in one regime or the other for centuries before rapidly switching back to the alternate state. Here the THC idea has little advantage over the global coupling idea. Although simplified climate models can simulate regime-like climate changes with abrupt transitions in between (Ganopolski and Rahmstorf 2001), this kind of behavior has not been found in coupled GCMs. Instead, after being forced to shutdown by a very large forcing, the THC in current coupled GCMs tends to dribble back to full strength over the following few centuries. In contrast, in the paleoclimate record, the resumptions of deep water formation appear more abrupt than the shut downs. For the global coupling idea the long residence in one climate state or the other and then a switch would, presumably, have to involve the deep ocean circulation. At some point deep ocean climate change reaches a point whereby its' influence on the coupled climate of the atmosphere and upper tropical oceans causes a switch between the different tropical climate states.

At this point the global coupling idea is 'faith-based'. However there are enough interesting new ideas on how the tropical Pacific both responds to, and organizes, global climate change, new theories on the role of tropical heat transports in global climate and new ideas on the global controls on the tropical thermocline to ensure that true believers will actively pursue this line in the future.

0.10 CONCLUSIONS

The abrupt climate changes that occurred during the last glaciation and deglaciation are mind-boggling both in terms of rapidity and magnitude. That winters in the British Isles could switch between mild, wet ones very similar to today and ones in which temperatures dropped to as much as 20° below freezing, and do so in years to decades, is simply astounding. No state-of-the-art climate model, of the kind used to project future climate change within the Intergovernmental Panel on Climate Change process, has ever produced a climate change like this. The normal explanation of how such changes occurred is that deep water formation in the Nordic Seas abruptly ceased or resumed forcing a change in ocean heat flux convergence and changes in sea ice. However coupled GCMs only produce such rapid cessations in response to unrealistically large freshwater forcing and have not so far produced a rapid resumption. Even when they do produce cessations of deep water formation the climate change around the North Atlantic region is much less than the proxy reconstructions indicate, even though the sea ice covers in the models increase.

According to coupled GCMs, cessations and resumptions of deep water formation do cause climate changes around the world akin to those reconstructed within the paleoclimate record. When the deep sinking branch of the THC in the North Atlantic is off, the Atlantic ITCZ moves south and the Asian monsoon weakens, both of which agree with reconstructions. However the modeled change in the Asian monsoon is weaker than that reconstructed while the North Atlantic Ocean circulation changes do not seem capable of causing the South American cooling seen in Andean ice cores for the most recent such abrupt change (the Younger Dryas).

Here we have tried to argue that the abrupt changes must involve more than changes in the North Atlantic Ocean circulation. In particular it is argued that the degree of winter cooling around the North Atlantic must be caused by a substantial change in the atmospheric circulation involving a great reduction of atmospheric heat transport into the region. Such a change could, possibly, be caused by a switch to a regime of nearly zonal wind flow across the Atlantic, denying western Europe the warm advection within stationary waves that is the fundamental reason for why Europe's winters are currently so mild. Such a change in wind regime would, presumably, also cause a change in the North Atlantic Ocean circulation as the poleward flow of warm, salty waters from the tropics into the Nordic Seas is diverted south by the change in wind stress curl. This would impact the location and strength of deep water formation and allow sea ice to expand south.

Both changes in the distribution and strength of tropical convection and, perhaps, changes in the temperature of the polar stratosphere, are capable of causing such changes in the mid-latitude wind regime, according to idealized GCM experiments. The tropical forcing route is appealing because the tropical climate change could help explain the large abrupt changes in the monsoons and tropical climate that are known to have occurred as well as force changes in mid-latitude atmosphere and ocean circulation and climate.

That the period of instrumental records has been free of dramatic abrupt changes, and that even the Holocene was quiet compared to the glacial period, argues that climate instability arises when there are continental ice sheets in North America and Eurasia and/or when the climate is colder. During glacial periods the climate can be described as fitting with Lorenz's (1968, 1970) concept of 'almost-intransitivity' in which the climate possesses successive very long periods with remarkably different states. It must be that either the presence of ice sheets, with their albedo and orographic forcing, or the colder mean state, allows the atmosphere and ocean circulations to adopt almost-intransitivity. It is possible that long integrations of coupled GCMs with glacial boundary conditions will reveal these states. Climate modelers should hesitate before discarding a model simulation that produces a climate that is distinctly warm in many parts of the world even in the presence of glacial boundary conditions!

Currently our knowledge of the general circulations of the atmosphere and ocean does not provide a means whereby we can imagine alternative states of the tropical and global climate, and the ability to move rapidly between them. However there has been enough recent work on the relationships between tropical atmosphere and ocean heat transports and the global controls on heat transports and the tropical thermocline to provide some hints that rearrangment may be possible. The situation is poised for a 'Manabe and Stouffer' moment when, with some clever, or fortuitous, experiment, alternative states are demonstrated in a model.

When, if ever, this will occur is unclear. The problem for dynamicists working in this area is that the period of instrumental observations, and model simulations of that period, do not provide even a hint that drastic climate reorganizations can occur. Our understanding of the general circulations is based fundamentally on this period, or, more correctly, on the last 50 years of it, a time of gradual climate change or, at best, more rapid changes of modest amplitude. Not surprisingly our understanding of the general circulations contains many ideas of negative feedbacks between the circulations that may help explain climate variability but also stabilize the climate (Bjerknes 1964, Hazeleger et al. 2005, Shaffrey and Sutton 2005). The modern period has not been propitious for studying how the climate can run away to a new state. Because of this our understanding has to be limited. Possibly the extent of our understanding will be brought into question by climate change itself as the Earth's climate changes more rapidly than we can extend our understanding of it. But we do not have to wait for that unfortunate event as the past is already full of events that simply cannot be placed within our current understanding of the general circulations but are there, waiting to be explained.

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