reason (Cane *et al.*, 1995). Regardless of the cause, the high degree of unforced variability makes it difficult to say with certainty that differences in the short coral records from different periods are not just due to sampling fluctuations. A modern example of the same problem arises from a coral record reported at the workshop by J. Cole, which shows lower frequency behavior in the mid–19th century than at present. The world was colder then; is there a causal relationship? The discrepancies noted above between the model and coral data at 2650 BP could be significant, or could just be due to limited sampling. By the same token, the agreement at earlier times could be fortuitous. More rigorous statistical analysis will sharpen the issue, and we plan to carry through such an analysis in the near future. However, it is most likely that this and similar issues can't be settled without more coral records. Finding the right fossil corals is in good measure a matter of luck. Moreover, fossil coral records tend to be rather short, exacerbating problems of interpretation. Another workshop talk, by C. Charles, illustrated a promising technique for overcoming this difficulty by joining series from different corals together, much as is done routinely for tree ring series. It appears realistic to believe that a coordinated program of modeling and fossil coral data acquisition could yield a reasonably complete picture of ENSO variations through the Holocene. Such a dataset would surely increase our understanding of ENSO dynamics, and our ability to tie ENSO variability to global changes through the Holocene.

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Abrupt Climate Change

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Any definition of 'abrupt' or 'rapid' climate changes is necessarily subjective, since it depends in large measure on the sample interval used in a particular study and on the pattern of longer term variation within which the sudden shift is embedded. Here, we avoid any attempt at a general definition but focus attention on different types of rapid transition found in the paleo-record in different time periods of the geologically recent past. Although distinctions between types are somewhat arbitrary, together they cover a wide range of shifts in dominant climate mode on timescales ranging from the last half million years to the last few centuries.

1. Over the past half million years, marine, polar ice core and terrestrial records all highlight the sudden and dramatic nature of glacial terminations, the shifts in global climate that occured as the world passed from dominantly glacial to interglacial conditions (e.g. Petit *et al.*, 1999). These climate transitions, although probably of relatively minor relevance to the prediction of potential future rapid climate change, do provide the most compelling evidence available in the historical record for the role of greenhouse gas, oceanic and biospheric feedbacks as nonlinear amplifiers in the climate system. It is such evidence for the dramatic effect of nonlinear feedbacks that, by very definition, supports the thesis that relatively minor changes in future climatic forcing may lead to dramatic, abrupt „surprises" in climatic response.

2. Within glacial periods, and especially well documented during the last one, spanning from around 110k to 11.6k years ago, there are dramatic climate oscillations, including high latitude temperature changes approaching the same magnitude as the glacial cycle itself, recorded in archives from the polar ice caps, high to middle latitude marine sediments, lake sediments and continental loess sections. These oscillations are usually referred to as Dansgaard-Oeschger Cycle and occur mostly on 1 to 2 kyr timescales (eg. Bender et al, 1999), although regional records of these transitions can show much more rapid change. The termination of the Younger Dryas cold event, for example, is manifested in ice core records from central Greenland as a near doubling of snow accumulation rate and a temperature shift of around 10°C occurring within a decade (Figure 1, Alley *et al.*, 1993). One hypothesis for explaining these climatic transitions is that the ocean thermohaline circulation flips between different stable modes, with warm intervals reflecting periods of strong deep water formation in the northern North Atlantic and vice versa (e.g. Stocker, 2000). It has been suggested that oscillation on this timescale is a persistent climatic feature which has continued throughout the Holocene, possibly including the Little Ice Age, albeit without the amplification associated with the presence of large Northern Hemisphere ice sheets (Bond *et al.*, 1999). Should this prove to be the case,

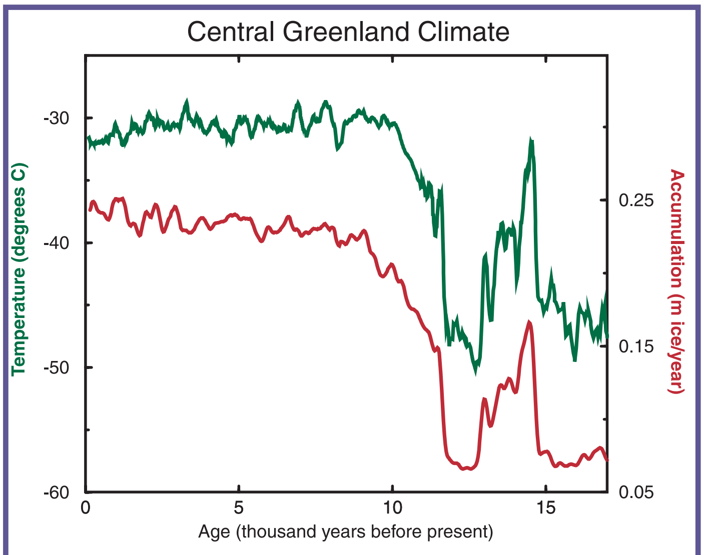

Figure 1: *The termination of the Younger Dryas cold event some 11.6k years ago was an abrupt climatic shift. In this record, from Central Greenland, it is manifested as a warming of around 10°C, accompanied by a doubling in annual precipitation volume, occurring in about a decade. Shown here are accumulation and oxygen isotope (shown as inferred temperature) records from the GISP2 ice core. (Source: Alley et al., 1993)*

the cycle would necessarily modulate higher frequency climate modes such as the NAO, and prediction of future climate trends in the North Atlantic region would require accounting for these longer timescale processes.

3. During the first half of the Holocene, from 11.6k to around 6k years ago, evidence from lower latitudes especially points to rapid shifts in climate during the period when global ice volume, sea-level and vegetation were changing in the wake of the last glacial termination. Many of the changes taking place during the early Holocene, including melting of the polar ice caps, the rise of global sea level to something approaching its present height, the recolonization of extensive areas by vegetation adapted to new climatic conditions and the maturation of soils resulting from increasingly stable vegetation cover, took millennia to complete. Thus, although it is tempting to use evidence of climate variability during the first half of the Holocene as an indication of possible 'warm climate surprises', for all the reasons just noted, it is important to remember that the period was one of transition. This said, it is equally important to dispel the view that the Holocene as a whole was a period of relatively constant climate. This proposition, arising from the stable isotope record in Central Greenland ice cores, is highly misleading. Not only is there now clear evidence of higher levels of climate variability during the Holocene in Greenland itself, but at lower latitudes, evidence for Holocene climate variability is very strong.

One example of early Holocene rapid climate change is the '8200 BP' cooling event recorded in the North Atlantic region (e.g. von Grafenstein *et al.*, 1998). One possible explanation for this dramatic regional cooling is a shutdown in the formation of deep water in the northern North Atlantic due to fresh water input caused by catastrophic drainage of Laurentide lakes (Barber *et al.*, 1999). If this explanation proves to be correct it would lend support to the conjecture, based on numerical modeling experiments, that formation of deep water in the North Atlantic is highly sensitive to the fresh water forcing. This in turn would tend to reinforce the possibility of a rapid cooling 'surprise' in the North Atlantic region associated with potential future changes in the hydrological cycle.

The whole of the early to mid-Holocene is marked by dramatic shifts in lake level and wetland extent in Africa and Central America. It is often difficult to gauge the pace of change from such records since many lakes in the region are, in part, the surface expression of ground water table variations the response time of which is likely to be quite long. Nevertheless, in terms of the temporal resolution available and the expression of the hydrological changes in the archives studied, the major shifts appear to be rapid and of high amplitude. Numerous modeling studies suggest that the abruptness of the onset and termination of the early to mid-Holocene humid period across much of Africa north of the equator, depends on the presence of nonlinear feedbacks associated with both ocean circulation and changes in surface hydrology and vegetation (e.g. deMenocal *et al.*, 2000). Without including these feedbacks alongside gradual insolation forcing, it is impossible for existing models to come even close to simulating the rapidity or the magnitude of climatic change associated with the extension of wetlands and plant cover in the Sahara/Sahel region prior to the onset of desiccation around 5500 BP.

4. For the last 6k years there are many more well dated high resolution records from a wide range of archives such as corals, tree rings and laminated lake sediments. There is also greater confidence in quantitative calibration through comparison with instrumental records. Thus the concept of rapid change becomes something which can be better quantified though it is worth noting that our perception of particular changes will depend on the total time frame within which they can be set. Thus what appears as a sudden shift in mode of variability over a period of decades may be seen as a transient event or part of an oscillating system on century or millennial timescales. The clearest examples of significant rapid shifts in climate during this period are most confidently discernible at regional scale or with respect to spatially constrained modes of variability, for example, the major changes in frequency and strength of ENSO events noted by Cane et al, (this issue). When, as is the case with the changes associated with the so-called Little Ice Age (LIA) and Medieval Warm Period (MWP), claims are made for at least hemispheric, if not global coherence, confirming widescale synchroneity becomes problematical (see Bradley, this issue).

Many temporally well resolved proxy records show climate variability beyond the range revealed in modern instrumental records from the same region. These records also include sudden shifts in mode. For example, Figure 2 shows a lake record from the central US which indicates a shift in the mode of hydrological variability occurred around 1200 AD, with the earlier portion of the record experiencing much more protracted and severe droughts than the later (Laird *et al.*, 1996).

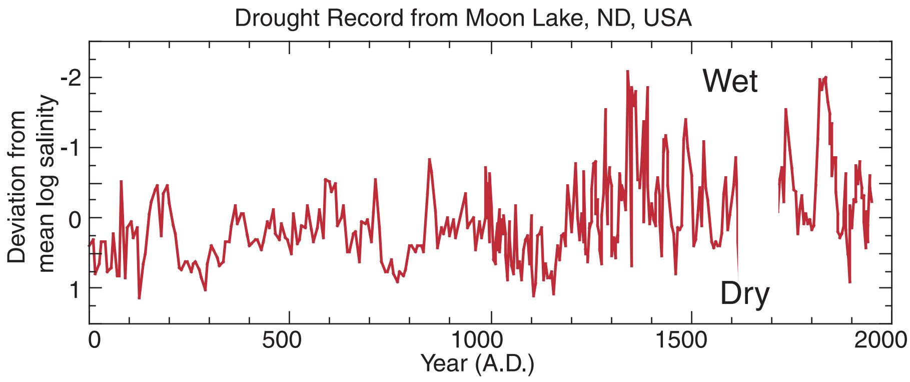

***Figure 2:** Lake salinity record reconstructed for Moon Lake, North Dakota, illustrating regional drought variability over the last 2000 years. The severe droughts of the 1930's and 1890's (positive inferred salinity) are well reconstructed, but are eclipsed by more extensive droughts before the beginning of the instrumental period. There is an abrupt change in drought variability around AD 1200. Before that time, the high plains were characterized by much more regular and persistent (e.g., interdecadal) droughts. The mechanisms for major shifts in drought variability of the past are not well understood, and no processes model has successfully simulated these types of changes. Note that the gap in 17th century data coverage represents absence of data. (Source: Laird et al., 1996)*

Although a thorough review is well beyond the scope of this note, these examples serve to highlight a wealth of evidence which exists for rapid climate changes during the Late Holocene; not always demonstrably globally or even hemispherically synchronous, but regionally highly significant. These changes are expressions of natural variability, the ongoing pattern of which will interact with and modulate the expression of any anthropogenic climate change effects. The underlying causes of the rapid changes now well documented remain uncertain in many cases. Some short term, extreme transient events clearly reflect the impact of major volcanic eruptions (Briffa,1998). In other examples, abrupt changes have been linked to ^{14}C anomalies, a likely proxy for solar activity, as is the case with the widespread, major changes documented around 2650 BP by Van Geel *et al.* (1996) and the sequence of drought episodes reconstructed for Ethiopia by Verschuren *et al.* (2000) from lake sediment records covering the last 900 years (Figure 3).

5. The past 200 years span the period of major human environmental perturbation. Over this period greenhouse gas concentrations have risen extremely rapidly to levels that are unprecedented in at least the past 400,000 years (e.g. Raynaud, 2000). The magnitude and rate of measured global temperature rise during the past 200 years, on the other hand, does not appear to be unusual within the context of the Holocene. During the same 200 year period, the rate of land cover change has probably also been unprecedented in the Holocene. The apparent ENSO phase shifts during the 1970's seems unique over this time period, and may thus represent a real climate shift (e.g. Trenberth and Hoar, 1997), although the available time series is probalby too short to unequivocally prove that the shift is significant (Wunsch, 1999). The inability to resolve questions of this kind from short instrumental time series provides one of the strongest arguments for extending the instrumental record of climate variability with well dated, temporally finely resolved and rigorously calibrated proxy data.

6. Implications for the future. Growing attention has been paid to the possibility of anthropogenic climate change leading to 'surprises' – shifts well beyond the range of variability upon which planning and construction schemes are based and even outside the envelope of projections generated by climate models. The paleorecord does not preclude such possibilities.

One such potential 'surprise' that has been the target of several recent modeling studies is a shut down of North Atlantic Deep Water production occurring as an indirect result of increasing greenhouse gas levels (Manabe and Stouffer, 1993) and possibly even in a manner sensitive to the *rate* of CO_2 increase (Stocker and Schmittner, 1997). Regional climate changes linked to such an event would certainly constitute a 'surprise' and, for many parts of the world, possibly even a catastrophe.

Another example is the possibility of greenhouse gas driven warming leading to a change in the frequency of ENSO events. Modeling studies indicate that a strong enhancement of ENSO conditions is not inconceivable (Timmerman *et al.*, 1999). Such a drastic shift in ENSO frequency would have enormous consequences for both the biosphere and humans. Paradoxically, one possible consequence might be a sufficient increase in E-P forcing over the subtropical Atlantic to stabilize the thermohaline circulation (Schmittner *et al.*, in press)

The messages from the paleorecord for the future are not limited to these examples. Nor is belief in anthropogenic greenhouse gas warming an essential prerequisite for heed-

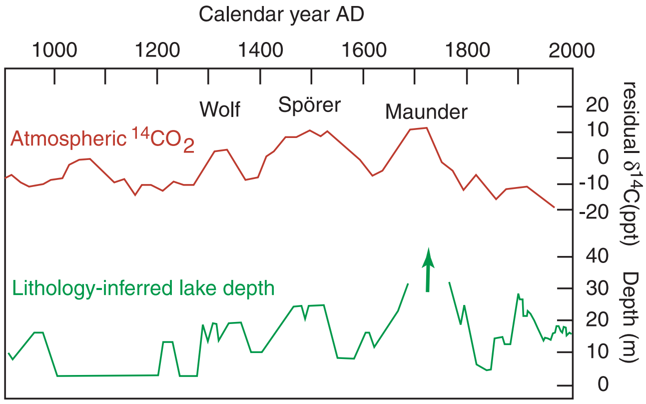

***Figure 3:** A comparison between inferred water depth in the Crescent Island Crater Lake, Ethiopia as an indicator of prolonged drought incidence, and the decadal record of atmospheric δ^{14}C production, a likely proxy for solar activity (Adapted from Verschuren et al., 2000).*

ing these messages. Extending the record of climate variability back through time reveals changes, often sudden and sometimes persistent on decadal to century timescales that lie outside the range of instrumental records. The concepts of future sustainability, water supply and food security may be dangerously short sighted if they fail to accommodate the evidence from the longer term record. This is especially the case in relation to changes in the magnitude and frequency of extreme events (e.g. Knox, 2000) and to shifts in hydrological regime (e.g. Hodell *et al.*, 1995; Messerli *et al.*, 2000). The growing consensus however, is that future climate change will reflect not only natural variability but anthropogenic forcing as well. It is interesting to compare even the most modest predictions of greenhouse warming with natural variability recorded in the recent past. Even though the last six centuries appear to have recorded both the coldest and warmest decades to have occurred in the late Holocene (e.g. Bradley, 2000), the amplitude of variation in Northern Hemisphere mean annual temperature between these extremes is less than the lowest projected temperature increases for the next century.

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Improving Estimates of Drought Variability and Extremes from Centuries-Long Tree-Ring Chronologies: A PAGES/CLIVAR Example

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The impact of severe drought on agriculture, water supply, and the overall environment is an increasing global concern as the demand for water outstrips supplies in many areas of the world. Reliable long-range forecasting methods need to be developed to allow agricultural and water resource planners and administrators to reduce the impact of future droughts. In addition, longer climate records are needed for improving regional drought risk assessments, especially those dealing with the rare, extreme events. For both purposes, the instrumental climate database is likely to be inadequate, even in the well monitored U.S. It is very difficult to know if the instrumental records are long enough to include the full range of drought variability likely to happen in any given region in the future. This issue was specifically addressed in a recent workshop convened by NOAA and NASA: "Assessing the Full Range of Central North America Droughts and Associated Landcover Change", Boulder, Colorado, June 2–4, 1999. One conclusion drawn from this workshop was that instrumental climate data over the U.S. are inadequate for capturing the "full range" of drought. Consequently, there is an urgent need to develop long records of past drought from a variety of proxy records. Among those available, precisely dated annual tree-ring chronologies from centuries-old trees growing on drought-stress sites are ideally suited for this pupose.

A recent paper by Woodhouse and Overpeck (1998) has likewise highlighted the limitations of instrumental climate data by examining the paleoclimate record of drought in the western U.S. They find evidence of past "megadroughts" of unusual severity and duration in the paleoclimatic record, ones that appear to have exceeded even the Midwestern "Dustbowl" drought of the 1930s. The analysis of Woodhouse and Overpeck (1998) illustrates the tremendous value of paleoclimate data in studying past drought. However, it also shows the current limitations of the available proxy records. Among the data they use is the 154 grid point network of well-calibrated and verified summer drought reconstructions from annual tree-ring chronologies produced by Cook *et al.* (1999) for the coterminous U.S. This network, based on the Palmer Drought Severity Index (PDSI; Palmer, 1965), provides a highly detailed record of drought and wetness over the U.S. in both space and time. Unfortunately, these reconstructions only extend back to 1700 at the present time. Yet, Woodhouse and Overpeck (1998) clearly show in a sparser collection of much longer individual drought reconstructions that some notable megadroughts occurred in the western US, mostly prior to AD 1600. Therefore, there is a great need to produce a substantially longer, high-density network of drought reconstructions for the U.S. that extends 600–800 years back into the past. Such a network would provide the means to carefully map the occurrence of drought during these megadrought periods. In so