during the MCA suggests that changes in the frequency or persistence of circulation regimes may account for the unusual nature of the period, and naturally this may have led to anomalous warmth in some (but not all) regions.

Numerous studies provide strong evidence that cooler conditions characterized the ensuing few centuries, and the term "Little Ice Age" is commonly applied to this period. Since there were regional variations to this climatic deterioration, it is difficult to define a universally applicable date for the "onset" and "end" of this period, but commonly ~A.D.1550–1850 is used (Jones and Bradley, 1992). However, there is evidence that cold episodes were experienced earlier, by A.D. 1450 or even A.D. 1250 in some areas (Grove and Switsur, 1994; Luckman, 1994). This definitional problem is illustrated by the estimates of Northern Hemisphere mean annual temperature for the last 1000 years, reconstructed by Mann *et al.* (1999) which show a gradual decline in temperature over the first half of the last millennium, rather than a sudden "onset" of a "LIA". Furthermore, it is clear that within the period 1550–1850 there was a great deal of temperature variation both in time and space. Some areas were warm at times when others were cold and vice versa, and some seasons may have been relatively warm while other seasons in the same region were anomalously cold. No doubt the complexity, or structure that we see in the climate of the LIA is a reflection of the (relative) wealth of information that paleoclimate archives (tree rings, corals, varved sediments, ice cores, historical records etc.) have provided for this period. Having said that, when viewed over the long term this overall interval was undoubtedly one of the coldest in the entire Holocene. Such is the nature of perspective – there is the danger that on close examination one may not see the woods for the trees, yet a full explanation of the observed changes may require a fairly detailed understanding of the temporal and spatial details. If we had similar data for the last 1000 years, our somewhat simplistic concepts of Medieval climatic conditions would certainly be revised and strong efforts are needed to produced a comprehensive paleoclimatic perspective on this time period. Only with such data will we be able to explain the likely causes for climate variations over the last millennium. At present, it is difficult to unequivocally ascribe the changes to external forcing (solar, orbital, volcanic) or internal ocean-atmosphere interactions, or indeed to a combination of all of these, perhaps varying in importance over time (cf. Mann *et al.*, 1998, 1999; Crowley and Kim, 1999; Broecker *et al.*, 1999). Given that these forcing factors will play a role in future climate variations, getting a better appreciation for both the past record of climate and of forcing factors must be a top priority for both PAGES and CLIVAR.

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ENSO Through the Holocene, Depicted in Corals and a Model Simulation

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In the 1990s El Niño attained global name recognition just short of Michael Jordan's. (Perhaps not coincidentally, the economic impact of the two is estimated to have the same order of magnitude, US$ 10^{10}). ENSO (El Niño and the Southern Oscillation) has also received enormous attention from the scientific community. Both the popular and scientific attention came in recognition of the premier role ENSO plays in modern climate variability, variability with great consequence for human society. A special recent concern, both popular and scientific, is whether the apparently "unusual" ENSO behavior of the past two decades is due to anthropogenic changes in the climate system. Or is it consistent with natural variability? It is hard to say from the instrumental record of ENSO, which is only some 130 years long.

Putting recent ENSO variability in proper context requires the longer view afforded by proxy records. This longer view includes periods with mean conditions and orbital forcings very different from today, providing some idea of the sensitivity of the ENSO system to external forcing. A number of reports on ENSO in the mid-Holocene appeared in the latter half of the 1990s. (McGlone *et al.*, 1995; Shulmeister and Lees, 1995; Sandweiss *et al.*, 1996, 1997; Wells and Noller, 1997; Gagan *et al.*, 1998) culminating in that of Rodbell *et al.* (1999). The interpretations they offered for the paleoproxy evidence are often contradictory, and have been much debated.

Clement *et al.* (2000) suggest a picture of the mid-Holocene (5000–10000 BP) tropical Pacific consistent with all prior paleo-ENSO data. Their view is based on a model simulation in which the intermediate Zebiak and Cane (1987) ENSO model, a model still in use for ENSO prediction, is forced by variations in heating due to orbital variations in seasonal insolation. Some summary statistics from the model run are presented in Figure 1. We see that the model ENSO

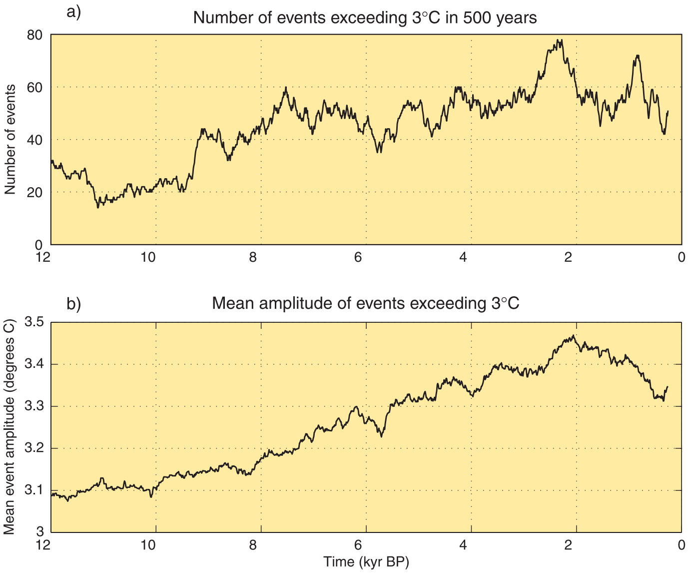

***Figure 1:** Results of a run of the Zebiak and Cane model for ENSO forced by departures of solar heating due to orbital variations. (For details, see Clement et al.1999). (a) The number of occurrences of warm (El Niño) events in 500 year overlapping windows (overlapping every 10 years). A warm event is defined to occur when the mean Dec–Feb SST anomaly in the NINO3 region (90°W–150°W, 5°S–5°N – the eastern equatorial Pacific) exceeds 3°C. (b) The mean amplitude of the warm events in the same overlapping 500 year windows.*

variability does not vanish in the mid-Holocene (in contrast, for example, to the interpretation of Sandweiss *et al.* 1996), but is weaker than in the modern period. ENSO events continue to occur roughly every 4 years, but there are fewer strong events (>3°C), and the mean amplitude of strong events is less than in the modern era. The mean model state in the eastern equatorial Pacific was colder than in the modern era, but this is due to lower temperatures in the warmest season (April at present); the coldest season temperatures are unchanged.

Ideally, the model should be compared to continuous records with annual resolution. Such a record, based on clastic layers in sediments from a lake in Ecuador, was provided by Rodbell *et al.* (1999). Clement *et al.*argue that since the clastic layers are caused by the heavy rains associated with strong El Niño events, the smaller number of these layers in the mid-Holocene is accounted for by the smaller number of strong El Niños. It is not necessary that the ENSO cycle cease entirely, only that it weakens. Sandweiss *et al.* (1996) proposed that the presence of tropical mollusks on the Peruvian coast indicates a permanent warm state. Clement *et al.* propose instead that the absence of strong cold (La Niña) events in this period keeps minimum temperatures warm enough for the mollusks to survive. An eastern Pacific with cooler maximum temperatures is consistent with the drier conditions on the coast of Peru indicated by Wells and others.

Because the Zebiak-Cane model is so simplified, certain physical interpretations of the results are immediate. The model includes only the tropical Pacific, so influences from the extratropics are excluded. Hence changes in its ENSO behavior can only be due to the *tropical* changes in the seasonal cycle of solar radiation. Orbital variations induce changes in the seasonal cycle of the coupled ocean-atmosphere system in the tropical Pacific. This changes the stability of the system, and since ENSO may be regarded as "just" an instability of this system (e.g. Tziperman *et al.*, 1994, 1997), ENSO behavior will change. Because the system is nonlinear, the changes in ENSO do not track the orbital variations in a straightforward way.

The simplified model is here being exercised in circumstances far from the modern setting for which it was constructed, so conclusions drawn from it must be tentative. Model aside, the scenario described above does appear consistent with the paleoproxy data, but this only underscores the fact that the data admits more than one interpretation. More definite conclusions require more data and more thorough model-data comparison.

The recent PAGES/CLIVAR Workshop on Climate of the Last Millennium (Venice, Nov 8–12, 1999) was an opportunity to begin comparing model results with coral records from the tropical Pacific. In many respects these corals provide the best ENSO proxy data we have. They come from the core ENSO region and their annual to subannual resolution captures ENSO's seasonal and interannual variability. Isotopic signals in these corals are known to be good proxies for sea surface temperature (SST), or, at the least, a combination of SST and rainfall. Even the combination is a rather direct measure of ENSO.

Figure 2 shows 3 oxygen isotope records from the north coast of Papua New Guinea: a modern record, a fossil coral dated at 2650 BP, and a fossil coral dated at 8400 BP (Tudhope *et al.*, manuscript in prep.) This region of the far western equatorial Pacific experiences relative drought and lowered sea surface temperatures (SSTs) during the El Niño phase of the Southern Oscillation. These climatic factors are recorded in the oxygen isotopic composition of the skeletons of corals growing in nearby reefs, with isotopically heavy skeleton (less negative $\delta^{18}O$) deposited during the dry and cool El Niño events. Consequently, isotopic analysis of the annually banded skeletons of large living and 'fossil' massive corals in the area can shed light on variations in the frequency and strength of ENSO.

Note the irregularity in all of these records. Strong and regular ENSO variability (~3–5 year periodicity) is evident from 1890 to 1925, and from the late 1960s until 1990, with a period of weak ENSO but large amplitude lower frequency variability in the intervening years (top panel). The 2,650 BP record (middle panel) shows modern-ENSO style variability (~3–5 year periodicity) in parts of the record, but much of the record is more like the weaker ENSO periods of the mid 20th century, and nowhere does the record show as extreme a change as occurred in the early 1940s. Differences in the 8,400 BP record (Figure 2 bottom panel) are more clear-cut: there is variability in the typical 2–7 year ENSO band, but it is much weaker than in the other two records.

Figure 3 (data from Gagan *et al.*, manuscript in prep.) compares a modern coral from the Australian Great Barrier Reef with a fossil coral from the same environmental setting dated at 6200 BP (note that on this figure El Niño conditions are up, in contrast to Figure 2). These multi-proxy records reveal the sequence of environmental changes within the annual cycle that is diagnostic of El Niño in the western Pa-

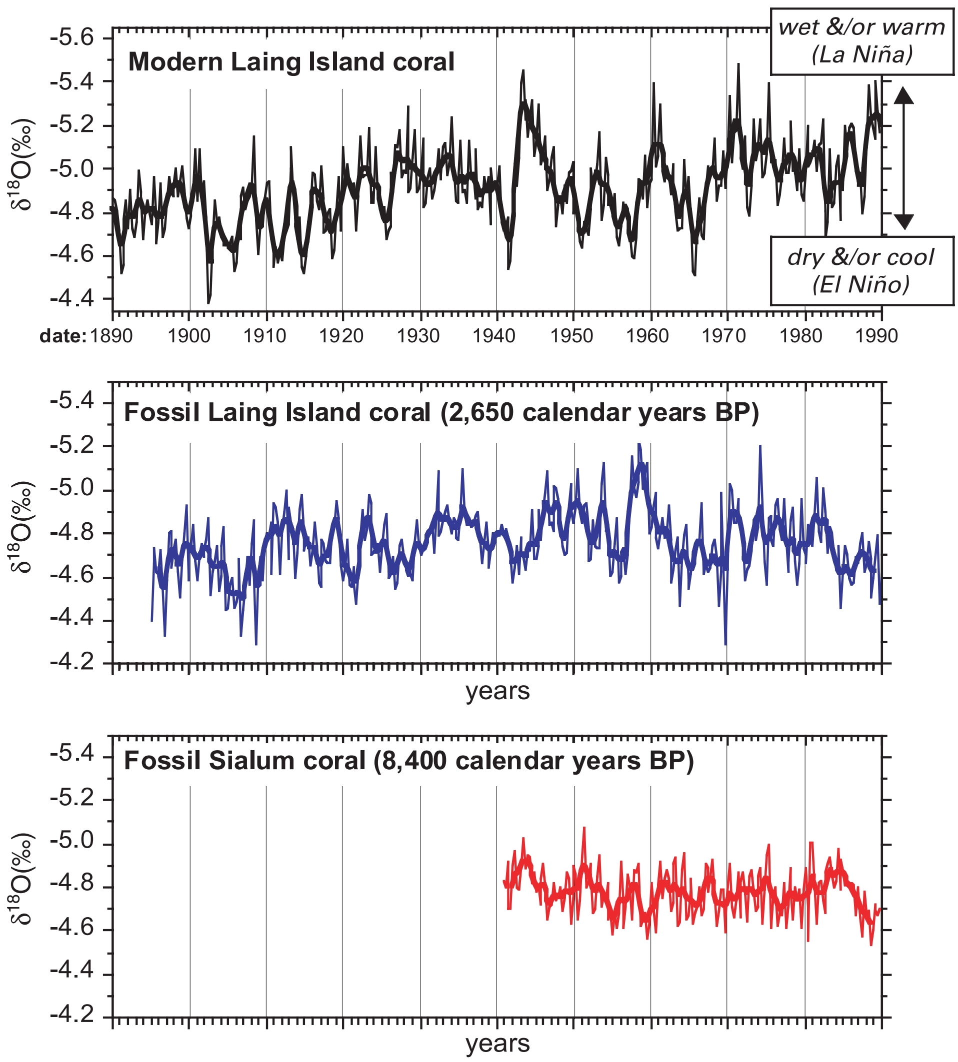

Figure 2:

Variability in ENSO in the Holocene revealed by a comparison of stable oxygen isotope records from living and Holocene Porites corals on the north coast of Papua New Guinea. Dating of fossil corals is by U-series alpha spectrometry. Data from: Tudhope et al, manuscript in prep.

Top Panel: One hundred year skeletal $\delta^{18}O$ record from a living coral at Laing Island (4°S, 146°E). Seasonal $\delta^{18}O$ data (thin line) has been smoothed with a 9pt binomial filter (thick line) to help reveal interannual variability. This coral data conforms with instrumental records of ENSO variations over this period.

Middle Panel: 95 year skeletal $\delta^{18}O$ record from a fossil coral at Laing Island dated to 2,650 calendar years BP.

Lower Panel: 50 year skeletal $\delta^{18}O$ record from a fossil, from Sialum (6°S, 148°E) coral dated to 8,400 calendar years BP. Modern corals from this Sialum site display similar amplitude ENSO variabilityto the Laing Island modern coral.

cific. Following the onset of El Niño, the 3-part sequence evident in the modern coral record includes: (i) relatively cool SSTs in the austral winter indicated by both the coral Sr/Ca and $\delta^{18}O$; (ii) reduced cloudiness in spring-summer indicated by the coral $\delta^{13}C$ values; and (iii) lower than average monsoon rainfall in summer shown by the $\delta^{18}O$. The strong El Niño events that are primarily confined to one annual cycle (1972/73, 1982/83, 1991/92) coincide with a strong 3-part signal in the coral record. At least 2 of the diagnostic indicators, usually cooler SSTs in winter followed by drought in summer, are observed during weak El Niños (1976/77, 1979/80, 1987/88).

Panel B in Figure 3 shows the same style of data for 6200 BP. In this 25 year long record, there is only one strong shift to El Niño. This event, in the middle of the record, clearly shows the 3 diagnostic features within the annual cycle that we know are associated with the development of an El Niño. The other 2 potential El Niños show winter SST cooling followed by drought, but the $\delta^{13}C$ signal is weak. Perhaps they are weak events. The record is short, but taken at face value it shows weaker and less frequent ENSO activity at 6200 BP than at present. Note too, that SSTs were ~1°C warmer and rainfall less variable than in the modern period, reminiscent of a more La Niña like state in the mean.

The model behavior shown in Figure 1 is in rough agreement with the coral records in showing weaker ENSO activity in the mid-Holocene (6250 BP and 8400 BP) than in the modern. The ENSO cycle does continue, but strong events are less frequent (longer periodicity). The model ENSO variability at 2650 is perhaps slightly stronger than in the modern era, while the coral record (Figure 2) is slightly weaker. Given the high degree of variability within each record, it is hard to say whether this discrepancy is more than an artifact of limited sampling.

Thus the coral records generally support the model based the scenario given above. The model results demonstrate the possibility that the weakening of ENSO in the mid-Holocene results solely from orbitally forced changes in the tropical Pacific. Impacts of the extratropics or remnants of the glacial era are not needed, and could be no more than second order influences.

The great variability within each of the sample records, coral or model, makes rigorous detailed comparison difficult. Even with constant forcing the model generates decadal and longer timescale variability. This model is known to be a chaotic dynamical system (Tziperman *et al.*, 1994). The same may well be true of the real system. Alternatively, the irregularity of the real ENSO may forced by atmospheric or oceanic noise. The record is too short to determine which is the

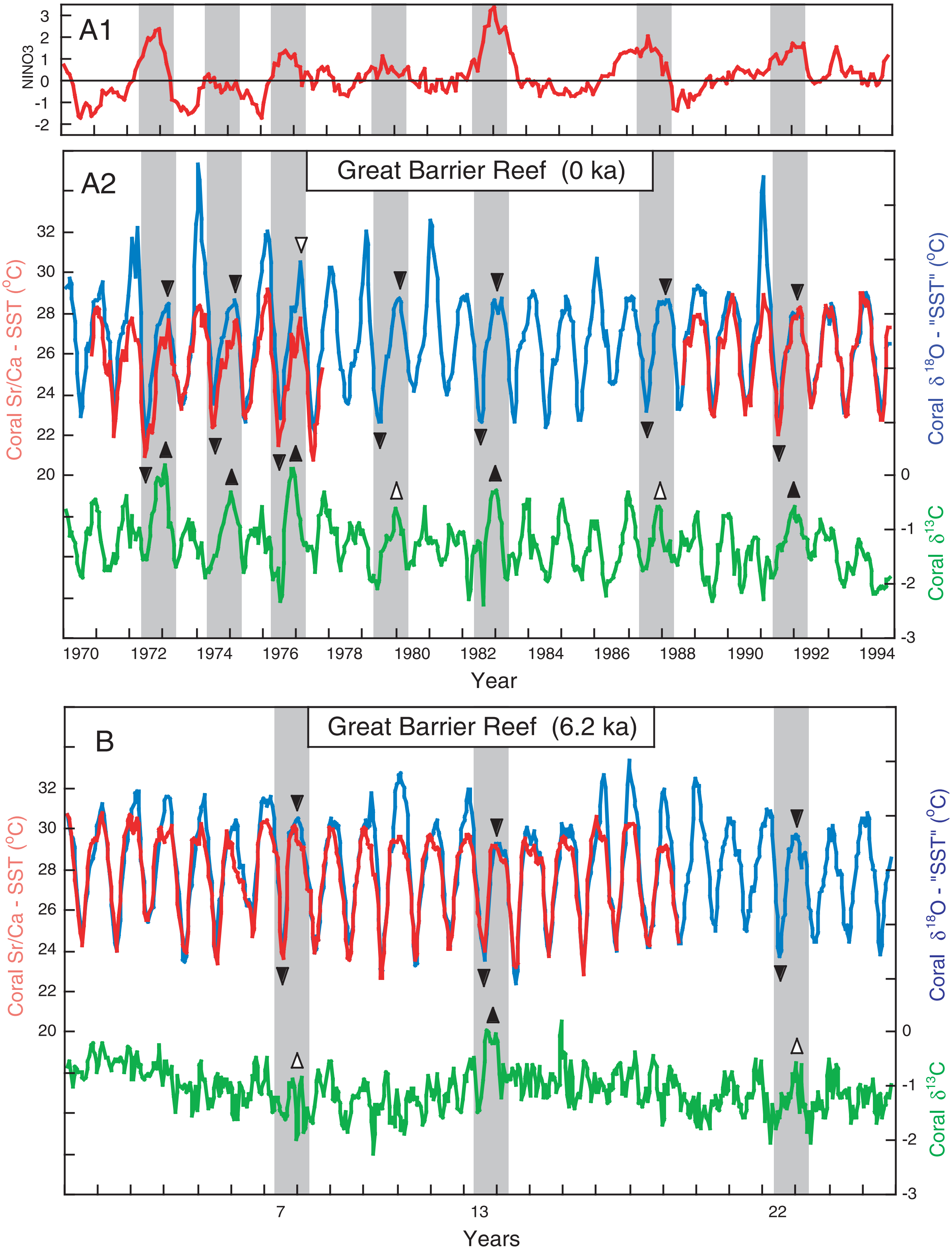

Figure 3:
A1: *SST anomalies for the eastern equatorial Pacific (5°N–5°S, 90°W–150°W) as an indicator of the timing and magnitude of El Niño events (stippled bars; from Kaplan et al., 1998).*

A2: *Seasonal changes in Orpheus Island, central Great Barrier Reef (18°45'S, 146°29'E) coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$. Stippled bars mark years containing the 3-part sequence of environmental changes in the Great Barrier Reef that is diagnostic of El Niño: (1) cooler SSTs in the austral winter indicated by the coral Sr/Ca and $\delta^{18}O$; (2) reduced cloudiness in spring-summer indicated by higher coral $\delta^{13}C$ values; and (3) reduced monsoon rainfall in summer indicated by the coral $\delta^{18}O$. Black arrows indicate strong responses; weaker responses are indicated in white.*

B: *Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ results for a mid-Holocene coral (TIMS ^{230}Th age = 6,184 ± 34 yrs) from the same reef environment as the modern calibration coral. The coral Sr/Ca and $\delta^{18}O$ data were converted to temperature as defined by Gagan et al. (1998) and the $\delta^{18}O$ data for the mid-Holocene coral have been adjusted by –0.47 per mil (see Gagan et al., 1998).*

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,