A Role for the Tropical Pacific Coupled Ocean-Atmosphere System on Milankovitch and Millennial Timescales. Part II: Global Impacts

Mark Cane and Amy C. Clement

Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York

We offer the hypothesis that global scale millennial and glacial cycles may be initiated from the tropical Pacific. Part I used model results to illustrate how nonlinear ocean-atmosphere interactions in the tropical Pacific could generate variations in the field of sea surface temperature (SST) on both orbital and millennial timescales. The physics underlying these variations is essentially the same as that causing ENSO (El Niño - Southern Oscillation) variability in the modern climate. Here we argue that, as with ENSO but on paleoclimatic timescales, these changes in SST distribution will be accompanied by changes in the location of atmospheric convection, which will alter the global climate via atmospheric teleconnections. By analogy with ENSO, it is hypothesized that the cold phase will increase the glaciation over North America, increase low cloud cover, and reduce atmospheric water vapor. All tend to cool the earth either by increasing the planetary albedo or reducing greenhouse trapping. The warm phase has the opposite tendencies.

We also critique the hypothesis that millennial changes are triggered by changes in the production of North Atlantic Deep Water.

1. INTRODUCTION

The discovery of global climate variations with millennial timescales is arguably the most profound paleoclimate surprise of recent decades. Though the observational picture is still quite incomplete, evidence is accumulating rapidly to show that these changes can set on abruptly, impact vast areas of the globe, and have existed through glacials and interglacials over the past 500,000 years. Illustrations abound in the present volume. Theory lags behind: it is fair to say that there are no compelling explanations for the causes of these millennial variations.

Here we propose a mechanism that locates the origin of these changes in ocean-atmosphere interactions in the tropical Pacific. The general idea may be grasped by analogy with the largest cause of climate variability in the modern period, ENSO (El Niño and the Southern Oscillation). ENSO is not a consequence of external forcings, but of coupled instabilities internal to the tropical Pacific ocean- atmosphere system. ENSO has global consequences because variations in the location of tropical convection perturb the global atmospheric circulation.

We hypothesize that the same physics operates on millennial timescales. In Part I of this two part study we presented evidence from a model calculation that the tropical Pacific interactions can induce fluctuations at these much longer timescales. Here we will argue that the global consequences of changes in the state of the tropical Pacific, which depend on relatively fast atmospheric physics, also operate at these longer timescales. Changes in the state of the tropical Pacific also may be forced by orbital variations (Clement et al, 1999). With

Mechanisms of Global Climate Change at Millennial Time Scales
Geophysical Monograph 112

orbital forcings the very large changes in the tropical Pacific are a consequence of its great sensitivity, whereas with millennial variations they are due to its outright instability. With either reason for the tropical Pacific changes, the global consequences follow. Our argument here applies to both millennial and Milankovitch variations. Evidence for or against it in one setting would likely apply to the other. However, our hypothesis is still crude and sketchy, and differences between the two cases will surely emerge as it is refined. For example, feedbacks from the extratropics to tropics should differ because of the direct influence of orbital variations on high latitudes.

It is worthwhile to recall that the state of knowledge a decade ago seemed to rule out a role for the tropics in causing any of the changes on paleoclimate timescales. According to the CLIMAP (1976) reconstruction of global sea surface temperature (SST), tropical temperatures at the Last Glacial Maximum (LGM) hardly differed from their present values. The largest changes were found in the North Atlantic, typically 10^oC and more, rendering much of the surface ice-covered. Further, the North Atlantic is the "source" of the global ocean circulation in that surface water there can become cold and salty enough to sink to the bottom and then spread globally. As it spreads it works its way back to surface, eventually returning to the North Atlantic to sink once again. This picture of a "conveyor" circulation is, of course, a vast simplification of the very complicated and nuanced global plumbing system that is the global ocean's thermohaline circulation, but it is a useful conceptual picture all the same.

A great deal of heat is associated with the conveyor, heat that is given up to the atmosphere when the water in the North Atlantic cools. Noting that deep water does not form in the Pacific, one may take the fact that Europe is several degrees warmer than corresponding latitudes in western North America as a measure of the power of the conveyor. There is strong evidence that the character of the conveyor has varied over the last 800 kyr (Broecker 1995 p171, Raymo et al. 1990), perhaps shutting down altogether at the LGM. It was argued that such a shutdown would surely cool Europe, and the rest of the world as well.

In the last two decades new data has enriched and occasionally changed the CLIMAP picture, providing facts to explain, new constraints on hypotheses for how the earth's climate system operates. Important among these:

(i) climate changes are often (usually?) abrupt;

(ii) there are many climate changes with periods of O(1 kyr) or more (e.g. Dansgaard-Oeschger cycles, Heinrich events) which have no obvious orbital pacing;

(iii) changes are global in extent, not just in the Northern Hemisphere, and not just near the poles;

(iv) many (most?) changes are globally simultaneous;

(v) the tropics cooled by 3^oC - 5^oC at the LGM.

This new information raises 2 new questions: Why are the changes abrupt? What drives the non-orbital (aperiodic) cycles? Both point to the fact that the response of the earth's climate system does not closely follow the orbital forcing.

Before beginning to address these questions, points (i) -(v) require a few comments. Evidence from ice cores (Johnsen et al. 1992, Grootes et al. 1993, Brook et al. 1996) indicates that in Greenland at least, "abrupt" can mean within a few decades. It is possible that changes are equally abrupt elsewhere, but the evidence doesn't allow us to say so with certainty. Though the orbital variations are complex, there is no obvious orbital signal significant enough to account for variations at periods shorter than 11 Kyr. It is particularly relevant to the arguments in this paper to note that the millennial variations are well documented in the tropics: for example, see Curry and Oppo (1997) for the Atlantic Ocean; Sirocko (1993) for the Indian Ocean; Linsley (1996) and Beck et al. (1997) for the Pacific Ocean. Changes over land in the tropics are indicated by methane variations (Chappellaz et al. 1993). Other references may be found thoughout the present volume. By stating that global variations are simultaneous, we only mean to say that many global changes happen at the same time to within the resolution of the age models for the data. We do not contradict such evidence as Blunier et al (1998) by claiming that all simultaneous changes are in the same sense (e.g. that all points on the globe warm or cool synchronously). ENSO provides a modern example of a set of simultaneous climate changes in which some parts of the globe get warmer while others cool, and some experience drought while others flood.

A colder tropics at once makes the North Atlantic a less viable cause and opens the possibility of a role for the tropics. The perspective being presented here would be unsupportable if the tropical SSTs were not appreciably different in glacial times, so we briefly review the evidence for it. There is not yet universal agreement that the CLIMAP version must be abandoned, but the preponderant evidence now favors a substantial tropical cooling in glacial times. The CLIMAP reconstruction is based on finding the relative abundances of different types of forminifera in sediment cores, and then estimating paleo SSTs from statistical relations derived from observations of the modern ocean. The assumption is that the relative abundances are indeed thermometers, and that they have not changed over time as so many other things have changed. The more foolproof paleothermometers, based on geochemical analyses (Sr/Ca, noble gases) indicate a cooling of $3-5^oC$. (Guilderson et al., 1994; Stute et al., 1995). The $\delta^{18}O$ difference, which at first seemed to agree with CLIMAP, implies much colder temperatures if one accepts pore water $\delta^{18}O$ changes as a measure of ice volume (Schrag et al., 1996). The influence of changing pH (Spero et al, 1997) may be another factor helping to reconcile the geochemical evidence. Measurements of $\delta^{18}O$ in ice cores from Peru and Tibet are additional evidence for colder tropical sea surface temperatures (Thompson et al., 1995; 1997).

There is also powerful physical evidence. Mountain snowlines descended in the tropics, suggesting that the whole atmosphere cooled, right down to the surface. The only other possibility is that the atmospheric lapse rate steepened, but it has proven difficult to construct a plausible scenario where the lapse rate changes and the SST hardly changes. The observed increase in large dust particles indicates stronger winds, and stronger winds implies colder SSTs – as in a modern La Niña. Finally, there was less CO2 in the atmosphere, and lower greenhouse gas content imples lower temperatures. An SST field consistent with the dominant evidence would be about 5^oC lower in the E Pacific and Atlantic, and close to 3^oC lower in the W Pacific and Indian Oceans. Among the many newer tropical estimates, only one, the alkenone data is not fully consistent. It indicates a change of about 2^oC all across the tropics, including the eastern Pacific.

2. A RECONSIDERATION OF THE ROLE OF THE NORTH ATLANTIC

At first these new facts regarding millennial timescale variability seemed to promote the importance of the North Atlantic and its conveyor circulation. Many of the observations supporting them come from the North Atlantic. Both theory and models shown that changes in salinity, generated either by glacial melting or by internal oscillations in the ocean, could cause the conveyor circulation to shut down abruptly. The North Atlantic would then cool, the nearby atmosphere would cool, and the climate would change – abruptly. However, it is now seen that on the whole these new facts cast some doubt on the paradigm with the North Atlantic led conveyor as prime mover. In addition to the questions raised at the Chapman Conference, it is noteworthy that in a recent article Broecker (1997), though not abandoning the conveyor circulation as a drier of millenial scale climate variability, argues for a central role for water vapor, a variable with a largely tropical source.

There is no doubt that there is a conveyor circulation in the modern ocean, and that it has varied in the past (e.g. Broecker, 1997). But not all the fluctuations observed in the climate system (e.g. each of the Dansgaard-Oeschger cycles) correspond to major conveyor changes.

How to have the changes be global and simultaneous is a difficult problem to solve via the conveyor (viz Broecker 1995 p. 258, also Broecker 1997]. Broecker (1997) has calculated the conveyor heat loss to be $3x10^{21}calyr^{-1}$, heat that goes to warm the atmosphere. This is a reasonable estimate of heat loss in the North Atlantic, but whether one should interpret it as a loss by the conveyor is open to interpretation. The North Pacific is not a deep water formation site, but nonetheless it gives up a great deal of heat to the atmosphere. Further, the evidence is that its exceptional for the conveyor to shut down totally . In its weak state waters continue to sink, but stop well short of the bottom, returning south at an intermediate depth (Boyle 1995, Broecker 1995 p.264). The change in the heating of the atmosphere is then only a fraction of the $3x10^{21}calyr^{-1}$ it would be for a total collapse of the conveyor.

While the conveyor carries a lot of heat by local standards, making a marked difference in the climate for those of us who live near the North Atlantic, it is not a lot of heat by global ocean measures. For example, the surface heat exchange difference between ENSO warm and cold phases is about $150Wm^{-2}$ over an equatorial Pacific area of about 20x 75 degrees of latitude and longitude, a difference in heat loss of $4.5X10^{19}calday^{-1}$. Each phase persists for about 200 days, yielding a change over the approximately 2 years between extremes of $9x10^{21}cal$.

No matter what it does to the deep ocean, the conveyor must change the temperature at the sea surface if it is to affect the atmosphere. It is difficult to see how changes in the conveyor could have an appreciable impact on the whole globe, as the paleo data now calls for. The easiest way would be to have the conveyor change the tropics, which would then change everything else. In order to give the conveyor an unrealistically favorable chance, let us confine ourselves to the tropical Pacific alone and imagine that all the 10 Sv ($10x10^6m^3s^{-1}$) estimated to leave the North Atlantic is piped directly to the surface layer (the top 50 m) of the tropical Pacific

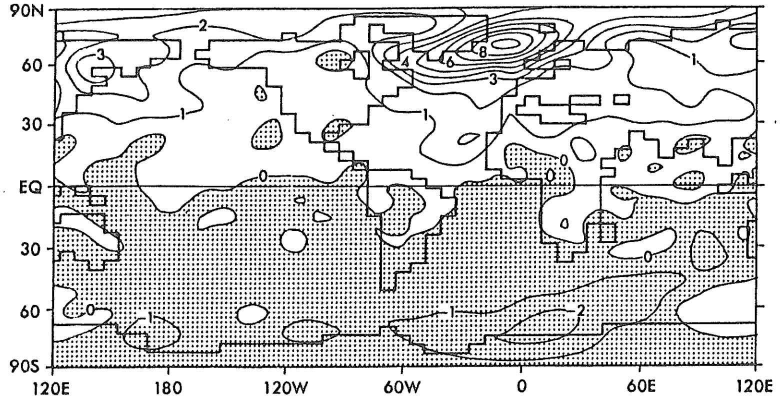

Figure 1. Difference in surface air temperature between a coupled GCM run with a strong thermohaline overturing in the North Atlantic and with no thermohaline overturning (from Manabe and Stouffer 1988).

(10^oNto10^oS, say). The consensus is that the rate of deep water formation is < 20 Sv, with approximately 10 Sv getting out of the N Atlantic across the equator; e.g. Speer and Tziperman (1992) estimate 9 Sv crosses the equator and consistent with that, they find the same amount of water crossing isopycnals. That is, about half of the 20 Sv is entrained locally in the N Atlantic, and recycled there. In fact, most of the goes to the southern ocean, and is much changed before it moves on to the rest of the world. At an input rate of 10 Sv it would take about 5 years to refill this tropical Pacific surface layer. Now suppose the conveyor switches off and this water supply suddenly becomes 7^oC colder. It would surely tend to cool the tropics, but meanwhile the surface heat exchange would be tending to warm the surface back to where it was; the e-folding time for this in the present climate is about 0.5 yrs (Seager et al 1988) – about 10 times faster than the conveyor is changing it. The net temperature change would only be about 0.6^oC in this fantastically favorable case.

This simple calculation is supported and extended by model calculations. There have been many model calculations, including some with comprehensive ocean-atmosphere coupled models, in which the conveyor is shut down and/or the North Atlantic SST is cooled (Rind et al 1986, Manabe and Stouffer 1988, Rahmstorf 1994, Tziperman 1997). A number of them are cited in papers advocating a major role for the conveyor in changing climate. Without exception they all show a strong impact in the areas adjacent to the North Atlantic, and little effect elsewhere on the globe (Figure 1). Some do show significant effects in polar latitudes of the Southern Ocean, and in the Kuroshio region. Thus these models, which include pathways through the atmosphere as well as the ocean, are unable to create a global impact.

One may also look to the modern data record, though with the caveat that it contains nothing in the North Atlantic as strong as the millennial oscillations. Still, the many data studies of the principle mode of climate variability there, the North Atlantic Oscillation, show strong signals around the North Atlantic and downstream of it, but nothing over the rest of the globe (e.g. Hurrell and van Loon, 1997). The pattern is consistent with model calculations, and may be taken as evidence that the atmospheric models do a credible job of simulating the response to SST variations in the North Atlantic.

A final problem with the North Atlantic centered view is the evidence that the global exchange between the surface and deep ocean goes on more or less unchanged even as the formation rates of NADW vary (cf. Broecker 1995) It appears that the other deep water sources in operation today, those around Antarctica, step up production and make up the difference. Its hard to see how the change in source could matter for the delivery of heat to the global surface layers.

3. A ROLE FOR THE TROPICAL PACIFIC

None of the foregoing denies that there are changes in the conveyor. We view them as part of the response to whatever is driving the climate system into new states. They are not the prime mover, but part of the chain of consequences. We now explore the possibility that this chain is set in motion from the tropical Pacific for both forced (orbital) and internal (Dansgaard-Oeschger) climate cycles.

Orbital or not, the incident global annual insolation is almost unchanged through these cycles. Since all these cycles last long enough to rule out significant heat storage, the net heat exchange to space must be close to zero. Even with orbital cycles, only the latitudinal and seasonal distributions of insolation at the top of the atmosphere change appreciably. Globally and annually averaged, the planet receives about the same energy input from the sun. Thus the heat leaving at the top of the earth's atmosphere also must be nearly unchanging. In order for this to occur at a cooler planetary temperature, the earth must either reflect more short wave (solar) radiation back to space via greater ice and snow extent, or more cloud cover; or trap less infrared radiation via less greenhouse gas (water vapor, CO2) or less cloud. Clouds have potentially conflicting roles, and, indeed, for reasons still mysterious, high clouds seem to exactly compensate the heat they reflect back to space by blocking the escape of longwave energy from below (Hartmann et al. 1992). Low clouds, however, yield a net cooling.

Our hypothesis is that both orbital variations and internal instabilities change tropical Pacific SST distributions. This change in the thermal boundary condition on the atmosphere alters the distribution of atmospheric heating in the tropics, which in turn alters the global climate. ENSO is the most familiar instance of such a mechanistic chain, but the physical links are quite general. Given a change in tropical Pacific SST distribution, the rest of the sequence works through the atmosphere and applies on all time scales intraseasonal and longer: centers of tropical convection tend to lie over the warmest water, so moving the locus of that water moves the convection; changing the location of the convection changes the teleconnection pattern – the impacts on distant locations (Hoerling et al 1997). ENSO provides clear examples. In a warm ENSO event (El Niño) the warm waters and the center of atmospheric convection move eastward from near Indonesia to the vicinity of the dateline. As a consequence northern North America warms. In a cold event (La Niña) the tropical Pacific warm pool contracts back toward Australasia, the convection follows, and northern North America typically is colder than average. Figure 2 illustrates for the recent warm event. Again, this chain of effects is not particular to ENSO. The atmospheric response time is short, and the same physics is known to work on intraseasonal timescales (Higgins and Mo 1997). Nor is there any reason why it would fail for longer time periods: numerical experiments with permanent anomalies show a very similar response (Kumar et al 1994).

Nor is the "ENSO physics" leading to tropical SST changes restricted to the ENSO cycle. As first suggested by Bjerknes (1969; for a succinct account see Cane 1991; for an update see Neelin et al 1998), a positive feedback operates in the coupled tropical Pacific ocean-atmosphere system. In the cold phase a stronger east-west SST gradient along the equator drives stronger easterly winds, which increase upwelling, thermocline tilt, and zonal currents, resulting in still stronger SST gradients. In the warm phase, a weaker SST gradient causes the winds to slacken which changes the ocean to further weaken the SST gradient. The ocean is too slow for this sequence to operate on intraseasonal timescales, but the equatorial ocean is fast enough to participate in variability on all timescales longer than the 4 years or so characteristic of the ENSO cycle. There is no obvious reason why this positive feedback should fail at millennial or orbital periods.

According to our present understanding ENSO is an internal instability of the tropical Pacific coupled ocean-atmosphere system (Neelin et al 1998). In this theory, ENSO variability in the modern climate record can be explained in terms internal to the climate system. Nonetheless, the same theory indicates that because of its sensitivity to the seasonal cycle in the tropics (Zebiak and Cane 1987, Tziperman et al. 1994) ENSO should be altered by orbital variations, especially precessional changes. The same physical links imply that the mean state of the tropical ocean-atmosphere also should change as the seasonal solar heating varies. This idea has been verified in a number of model studies (Dijkstra and Neelin 1995, Clement et al 1996).

Thus there is a reasonable expectation for tropical Pacific variability on orbital timescales. The model runs reported in Part I were intended to check this expectation. Briefly, the same Zebiak and Cane (1987) model in use for more than a decade to study and predict ENSO was run for 150,000 years, imposing the anomalies in solar heating due to orbital variations (see Clement et al. 1999 in addition to Part I). In response, the model shows increases or decreases in the frequency of ENSO warm or cold events, and changes in their average amplitudes. In some orbital states there are more warm events, in some more cold events, in some fewer extremes of either sign. Along with such variations go changes in average SST and thus in the mean position of the warmest SSTs. The changes in SST regime, which often take less than

1000 years, are more abrupt than the orbital variations, though not so abrupt as the changes observed in the Greenland ice core.

Surprisingly, this model run also showed more power at millennial timescales than would be expected just from random fluctuations of a process with its power concentrated at typical ENSO timescales (see Part I). This excess power must arise from nonlinear interactions within the model system, not as the red noise extension of the subdecadal ENSO cycle. Nor can it arise from external causes: the excess millennial power is even more impressive in a 150,000 year run with orbital parameters fixed at present day values (see Fig. 5 of Part I).

These runs do show peaks at periods near 1500 years, similar to those in the paleoclimate record, (viz Fig. 5 of Part I). However, as discussed in Part I (viz Fig. 6 there), the most reasonable interpretation of the model run is that while there is broad band power at millennial periods, any peaks are just artifacts from too short a record. We suspect that the same is true of the paleoclimate record, which supports the idea of these fluctuations stemming from internal instabilities rather than external forcings. The observations showing marked peaks extend for no more than a few 10s of kyrs, too short to resolve peaks around 1500 years. Moreover, different paleoproxies show somewhat different peaks, and the one record extending for several 100 ky, long enough to isolate millennial peaks, shows the very many peaks one would expect if the true process is broad band (Oppo et al 1998). On the other hand, we cannot absolutely rule out the possibility that there is truly a single strong peak or a few strong peaks, split into many peaks in the observational record by errors in the age model used in converting from sediment core depth to time.

The highly simplified Zebiak and Cane model was not designed with paleoclimate variations in mind, and we do not interpret these runs in any detail. (Part I discusses model limitations.) We use the model results here solely to illustrate two ideas that may be derived from a consideration of the physics of the coupled ocean-atmosphere system. First, the orbital variations alter the seasonal cycle which exerts such a powerful influence on tropical Pacific interannual variability. Consequently, the tropical Pacific may vary on orbital timescales independent of influences from the rest of the climate system. Second, in common with other nonlinear systems (cf Lorenz, 1991), the tropical Pacific ocean-atmosphere may exhibit regime like behaviors which persist far longer than any obvious intrinsic physical timescale. Consequently, the tropical Pacific may vary on millennial timescales independent of influences either from within the rest of the climate system or from external causes.

The crucial issue for the rest of the climate system is the locus of atmospheric convection in the tropics. In the present climate we know that different locations have different implications for the impact on higher latitudes, and these would presumably be influenced by other differences between the glacial atmospheric circulation and the modern. We are not at all confident that our simple model yields a trustworthy notion of where the center of convection moves as the orbital configuration varies, or where it is during the stadial and interstadial phases of the millennial cycles. Currently, the best documented description is that for the ENSO cycle. In the warm (El Niño) phase, convection moves with the warmest water into the central Pacific, in the vicinity of the dateline. In the cold (La Niña) phase the warm pool contracts and the convection moves back over the Indonesian region. We describe some of the warm phase response; the cold phase response is roughly (sometimes very roughly) opposite (see Hoerling et al 1997 for an account of the differences).

Figure 2 illustrates one well known influence of El Niño, a warming of northern North America. An interesting if somewhat anecdotal confirmation is based on Hudson Bay Trading Company records of the date that the ice goes out on Hudson Bay (Moodie and Catchpole, 1975). Hamilton and Garcia (1986) showed that in El Niño years the ice goes out early. In view of the broad spatial scale of the teleconnection pattern, the implication is that moving the convection to the central Pacific will help to melt ice and snow in Canada, while positioning it in the far western Pacific will favor ice sheet growth. Extrapolating, moving the convection to the far west for a long enough period will help to grow a Laurentide Ice Sheet, while the state resembling El Niño will tend to melt it. If the pattern of ENSO teleconnections resembled the present one, variations in the southern edge of the ice sheet would accompany millennial cycles.

Something of a case can be made for the ENSO cycle having the proper impacts on the other albedo/greenhouse influences listed above. Satellite based cloud climatologies (Rossow and Schiffer 1991) show a tendency toward less low cloud during warm events (Figure 3), when the tropical area covered by cold waters is at a minimum. This tendency is consistent with the results of Klein and Hartmann (1993), who suggest that there will be more low cloud with a strengthening of the inversion at the top of the atmospheric boundary layer. As illustrated in

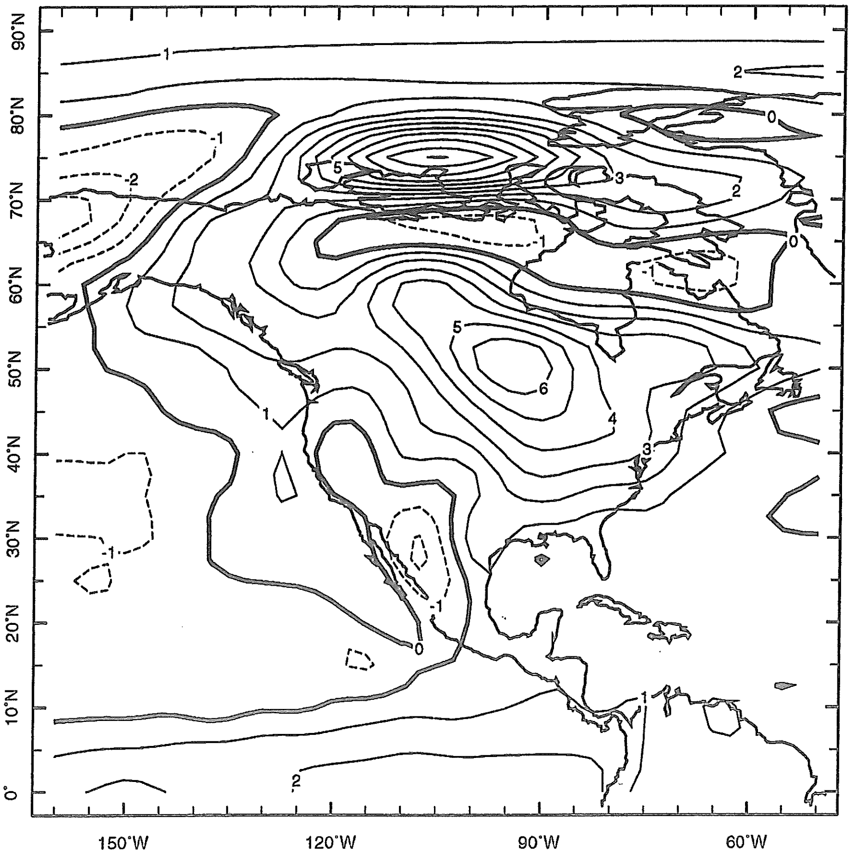

Figure 2. 1000 mb temperature anomalies for December 1997 to February 1998.

Figure 4 from Soden (1997) there is also some evidence for an increase in atmospheric water vapor during warm events (also see Sun and Oort 1995). These changes are small in amplitude, but they all line up in the right sense for El Niño like heating to favor interglacial conditions and La Niña like heating to favor glacial conditions. In the modern record, only atmospheric CO_2, which decreases during El Niño events, appears to be out of line. However, it may be that the decrease is short-lived, and that the long term impact of El Niño events is a net increase (Keeling et al, 1995; Rayner et al, 1999). (Also see Anderson et al. (1990), whose study of pleistocine marine varves off California led them to suggest that more CO_2, may be sequestered in the ocean when cold event conditions prevail.) A more complete model of the global climate system will be needed to see if these effects can trigger the substantial changes observed in millennial and orbital timescale climate records.

The limitations of the model render it silent on the question of how the rest of the world will feed back on the tropical Pacific. Earlier studies of the role of the tropics in paleoclimate have emphasized the changes in the monsoons (Kutzbach and Liu 1997, Lindzen 1993, Lindzen and Pan 1994). The evidence that the monsoons change with orbital variations is compelling, and it is highly likely that these changes would influence the tropical oceans. Once the higher latitudes have cooled appreciably, there is likely to be an impact on the tropical Pacific, either through the ocean (Bush and Philander 1998) or the atmosphere (Broccoli 1998). Thus, we must remain open to the possibility that feedbacks onto the tropical Pacific will alter the picture substantially. At present we cannot say whether they are more likely to reinforce or to interfere with the local feedbacks.

In addition to its regional limits, the model is an anomaly model, calculating only changes from the modern climate. By construction it is constrained to stay near the present climate, so its responses to orbital changes and its millennial variations are likely to be understated versions of reality. They are best taken as

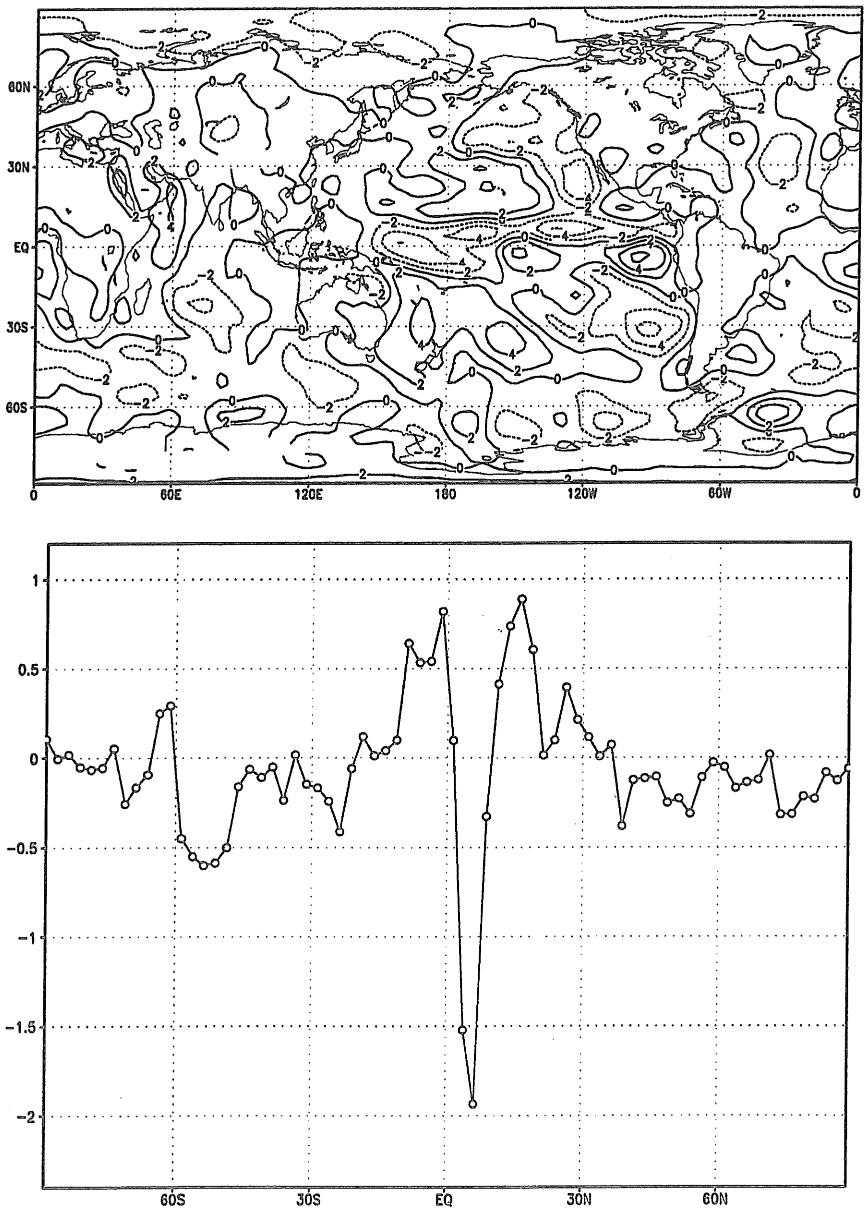

Figure 3. (a) Low cloud frequency from ISCCP for warm event years (1986, 1987 averaged from July-June) minus cold events years (1984,1988). (b) Zonal average of (a).

illustrations of possible behaviors rather than as literal predictions of the paleoclimate record. Further experiments with more complete models will be needed to build confidence in the idea that the tropical Pacific is a substantial driver of paleoclimate variations.

It will be important to develop a solid notion of where the center of convection moves as the orbital configuration varies, where it is during the stadial and interstadial phases of the millennial cycles. Different locations have different implications for the impact on higher latitudes, though these would presumably be influenced by other differences between the glacial atmospheric circulation and the modern.

In addition to more modeling work, there is a need for more observational studies. Most of the paleoclimate record comes from higher latitudes, especially the North Atlantic. There is a strong need for a more complete picture of the tropical Pacific. What can be said

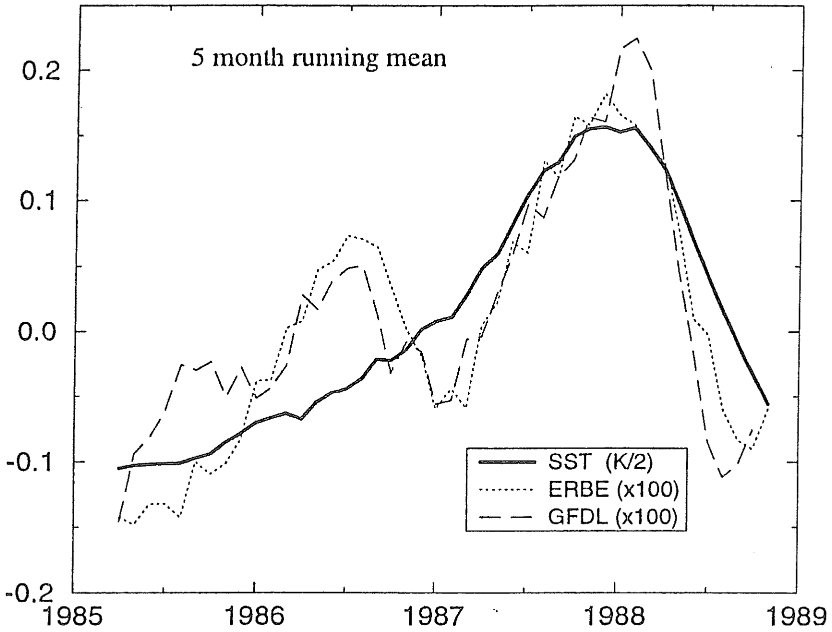

Figure 4. A time series of the tropical-mean interannual anomaly of fractional greenhouse trapping (which removes the effect of the change in surface temperature on greenhouse trapping) for ERBE observations dotted, for the GFDL GCM simlulations, dashed, and observed SST anomaly, solid (from Soden 1997).

about the changes in SST, east and west? How did the thermocline depth and slope vary over time? Can these changes be synchronized with changes in the tropical Atlantic and Indian Oceans, as well as with high latitude observations?

As with the North Atlantic hypotheses, the tropical scenario is neither complete and nor problem free. Interactions with the rest of the global climate system must be spelled out. Even granting that the tropical Pacific influences glacial growth and decay in North America, variations in Northern Hemisphere summer insolation must have an influence as well, and the proper accounting of the combined impact of the two is needed. Even if the North Atlantic is not the prime mover, there is no doubt that proxies in that region have recorded large changes during millennial and orbital cycles, changes that any theory must explain. While it is true that ENSO's impacts are nearly global, the North Atlantic and Europe are among the the places it seems to largely miss. It is not a complete miss (Davies et al. 1997; Rogers 1984), and recently Huang et al (1998) have suggested that there is a coherent impact on the NAO when the Pacific anomalies are strong. There is no obvious strong direct connection from the tropical Pacific, but an indirect mechanism is a possibility For example, one may argue from the well established fact that there is an ENSO impact on the tropical Atlantic, and the increasing evidence that the North Atlantic Oscillation, which has strong signals in Europe as well as its eponymous region, can be driven from the low latitude Atlantic (Robertson et al. 1999).

It is premature to make strong claims for the tropical Pacific hypothesis sketched here. The causal chain from the tropical Pacific to millennial scale variability still has serious gaps and weaknesses, though arguably no worse than other proposed explanations for the expanded inventory of paleoclimate cycles. However, paleoclimate evidence indicates that these cycles are global, including the tropics, and quite often globally synchronous, so our understanding and observations of modern climate make it hard to see how an adequate scenario for paleoclimate variations can be constructed without the tropical Pacific as a player. Even at this early stage, the perspective presented here points in a new direction for modeling and observational studies, one that uses our ideas of modern climate variability as a guidepost.

Acknowledgments. We thank two anonymous reviewers and our editor, Robin Webb, for constuctive suggestions that substantially improved the paper. This work was supported by National Science Foundation Grant No. ATM 92-24915.

REFERENCES

Anderson, R., Linsely, B., and Gardner, J. (1990). Expression of seasonal and enso forcing in climate variability at lower than enso frequencies: evidence from pleistocene marine varves off california. *Paleogeo. Paleoclim. Paleocean.*, *78*, 287–300.

Beck, J., Récy, J., Taylor, F., Edwards, R. L., and Cabioch, G. (1997). Abrupt changes in the early Holocene tropical sea surface temperature derived from coral records. *Nature*, *385*, 705–707.

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, *97*, 163–72.

Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T., Raynaud, D., Jouzel, J., Clausen, H., Hammer, C., and Johnsen, S. (1998). Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature*, *394*, 739–743.

Boyle, E. A. (1995). Last Glacial Maximum North Atlantic deep water- on, off, or somewhere in between. *Phil. Trans. Roy. Soc.*, *348*, 243–253.

Broccoli, A. (1998). Extratropical Influences on tropical paleoclimates . *AGU Monograph: Mechanisms of millenial scale global climate change.* submitted.

Broecker, W. (1995). *The glacial world according to Wally.* Eldigio, Palisades, NY. p.318.

Broecker, W. (1997). Thermohaline circulation, the Achilles heel of our climate system: will man made CO_2 upset the current balance? *Science*, *278*, 1582–1588.

Brook, E., Sowers, T., and Orchardo, J. (1996). Rapid variations in atmospheric methan concentration during the past 110,000 years. *Science*, *273*, 1087–1091.

Bush, A. and Philander, S. (1998). The role of ocean-atmosphere interactions in tropical cooling during the last glacial maximum. *Science*, *279*, 1341–1344.

Cane, M. A. (1991). Forecasting El Niño with a Geophysical Model. In Glantz, M., Katz, R., and Nicholls, N., editors, *Teleconnections Linking Worldwide Climate Anomalies.*, chapter 11, pp. 345–369. Cambridge U. Press, Cambridge, England.

Chappellaz, J., Blunier, T., Raynaud, D., Barnola, J., Schwander, J., and Stauffer, B. (1993). Synchronous changes in atmospheric CH_4 and Greenland climate between 40 and 8 kyr BP. *Nature*, *366*, 443–445.

Clement, A. C., Seager, R., and Cane, M. A. (1999). Orbital controls on the tropical climate. *Paleoceanography.* accepted.

Clement, A. C., Seager, R., Cane, M. A., and Zebiak, S. E. (1996). An ocean dynamical thermostat. *J. Climate*, *9*, 2190–2196.

Curry, W. B. and Oppo, D. (1997). Synchronous, high-frequency oscillations in the tropical sea surface temperatures and North Atlantic Deep Water production during the last glacial cycle. *Paleoceanography*, *12*, 1–14.

Davies, J., Rowell, D., and Folland, C. (1997). North Atlantic and European seasonal predictability using an ensemble of multidecadal atmospheric GCM simulations. *Int. J. Clim.*, *17*, 1263–1284.

Dijkstra, H. A. and Neelin, J. D. (1995). Ocean-atmosphere interaction and the tropical climatology. Part II: Why the Pacific cold tongue is in the east. *J. Climate*, *8*, 1343–1359.

Grootes, P., Stuiver, M., White, J., Johnsen, S., and Jouzel, J. (1993). Comparison of oxygen-isotope records from the GISP2 and GRIP Greenland ice cores. *Nature*, *366*, 552–554.

Guilderson, T. P., Fairbanks, R. G., and Rubenstone, J. L. (1994). Tropical temperature variations since 20 000 years ago: Modulating interhemispheric climate change. *Science*, *263*, 663–665.

Hamilton, K. and Garcia, R. (1986). El Nino Southern Oscillation Events and their associated mid latitude teleconnections 1532-1828 . *Bull. Am. Soc.*, *67*, 1354–1361.

Hartmann, D. L., Ockert-Bell, M. E., and Michelsen, M. (1992). The effect of cloud type on Earth's energy balance: Global analysis. *J. Climate*, *5*, 1281–1304.

Higgins, R. and Mo, K. (1997). Persistent North Pacific circulation anomalies and the tropical intraseasonal oscillation. *J. Climate*, *10*, 223–244.

Hoerling, M.P., A. K. and Zhong, M. (1997). El Niño, La Niña, and the nonlinearity of their teleconnections. *J. Climate*, *10*, 1769–1786.

Huang, J., Higuchi, K., and Shabbar, A. (1998). The relationship between the North Atlantic Oscillation and El Nino Southern Oscillation. *Geophys. Res. Lett.*, *25*, 2707–2710.

Hurrell, J. W. and van Loon, H. (1997). Decadal Variations in Climate associated with the North Atlantic Oscillation. *Climatic Change.* In press.

Johnsen, S., Clausen, H., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C., Iversen, P., Jouzel, J., Stauffer, B., and Steffensen, J. (1992). Irregular glacial interstadials recorded in a new Greenland ice core. *Nature*, *359*, 311–313.

Keeling, C.D. and Whorf, T.P. and Wahlen, M. and Vanderplicht, J. (1995). Interannual extremes in the rate of rise of atmospheric carbon-dioxide since 1980. *Nature*, *375*, 666–670.

Klein, S. A. and Hartmann, D. L. (1993). The seasonal cycle of low stratiform clouds. *J. Climate*, *6*, 1587–1606.

Kumar, A., Leetmaa, A., and Ji, M. (1994). Simulations of atmospheric variability induced by sea-surface temperatures and implications for global warming. *Science*, *266*, 632–634.

Kutzbach, J. and Liu, Z. (1997). Response of the African monsoon to orbital forcing and ocean feedbacks in the Middle Holocene. *Science*, *278*, 440–443.

Lindzen, R. S. (1993). Climate dynamics and global change. *Ann. Rev. Fluid Mech.*, *26*, 353–278.

Lindzen, R. S. and Pan, W. (1994). A note on orbital control of equator-pole heat fluxes. *Clim. Dyn.*, *10*, 49–57.

Linsley, B. (1996). Oxygen isotope evidence of sea level and climatic variations in the Sulu Sea over the past 150,000 years. *Nature*, *380*, 234–237.

Lorenz, E. (1991). Chaos, spontaneous climatic variations and detection of the Greenhouse effect. In Schlesinger, M. E., editor, *Greenhouse-Gas-Induced Climate Change: A Critical Appraisal of Simulations and Observations*, pp. 445–453. Elsevier, Amsterdam, the Netherlands.

Manabe, S. and Stouffer, R. (1988). Two stable equilibria of a coupled ocean-atmosphere model. *J. Climate*, *1*, 841–866.

Moodie, D. and Catchpole, A. (1975). Environmental data from historical documents by content analysis . *Manitoba Geographical Studies*, *5*, 1–119.

Neelin, J. D., Battisti, D., Hirst, A., Jin, F., Wakata, Y., Ymamgata, T., and Zebiak, S. (1998). ENSO Theory . *J. Geophys. Res.*, *103*, 14261–14290.

Oppo, D., McManus, J., and Cullen, J. (1998). Abrupt climate events 500,000 to 340,000 years ago: evidence from subpolar North Atlantic sediments. *Science*, *279*, 1335–1338.

Rahmstorf, S. (1994). Rapid climate transitions in a coupled ocean-atmosphere model. *Nature*, *372*, 82.

Raymo, M., Ruddiman, W., Shackleton, N., and Oppo, D. (1990). Atlantic-Pacific carbon isotope differences over the last 2.5 million years. *Earth Planet. Sci. Lett.*, *97*, 353–368.

Rayner, P.J., Law, R.M., and Dargaville, R. (1999). The relationship between tropical CO2 fluxes and the El Niño-Southern Oscillation. *Geophysical Research Letters*, *26*, 493–496.

Rind, D., Peteet, D., Broecker, W., McIntyre, A., and Ruddiman, W. R. (1986). The impact of cold North Atlantic sea surface temperature on climate: implication for Younger Dryas cooling (11-10 k). *Climate Dyn.*, *1*, 3–33.

Robertson, A. W., Mechoso, C. R., and Kim, Y. (1999). The influence of Atlantic sea surface temperature anomalies on the North Atlantic oscillation. *J. Climate.* submitted.

Rogers, J. (1984). The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon. Wea. Rev.*, *112*, 1999–2015.

Rossow, W. B. and Schiffer, R. A. (1991). ISCCP cloud data products. *Bull. Am. Meteor. Soc.*, *72*, 2–20.

Schrag, D., Hampt, G., and Murray, D. (1996). Pore fluid constraints on the temperature and oxygen isotopic composition of the glacial ocean. *Science*, *272*, 1930–1931.

Seager, R., Zebiak, S. E., and Cane, M. A. (1988). A model of the tropical Pacific sea surface temperature climatology. *J. Geophys. Res.*, *93*, 1265–1280.

Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M, and Duplessy, J.C (1993). Century-scale events in monsoonal climate over the past 24,000 years. *Nature*, *364*, 322–324.

Soden, B. J. (1997). Variations in the tropical greenhouse effect during El Niño. *J. Climate*, *10*, 1050–1055.

Speer, K. and Tziperman, E. (1992). Rates of water mass formation in the North-Atlantic ocean. *J. Phys. Oceanogr.*, *22*, 93–104.

Spero, H., Bijma, J., Lea, D., and Bemis, B. (1997). Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes . *Nature*, *390*, 497–500.

Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J., Schlosser, P., Broecker, W., and Bonani, G. (1995). Cooling of tropical Brazil during the last glacial maximum. *Science*, *269*, 379–383.

Sun, D.-Z. and Oort, A. H. (1995). Humidity-temperature relationships in the tropical troposhere . *J. Climate*, *8*, 1974–1987.

Thompson, L., Mosley-Thompson, E., Davis, M., Lin, P., Cole-Dai, J., and Bolzan, J. (1995). A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability . *Ann. Glaciol.*, *21*, 175–185.

Thompson, L., Tao, T., Davis, M., Henderson, K., Mosley-Thompson, E., Lin, P., Beer, J., Synal, H., Cole-Dai, J., and Bolzan, J. (1997). Tropical climate instability: The last glacial cycle from a Qinghai- Tibetan ice core. *Science*, *276*, 1821–1825.

Tziperman, E. (1997). Inherently unstable climate behavior due to weak thermohaline circulation. *Nature*, *386*, 592–595.

Tziperman, E., Cane, M. A., and Zebiak, S. E. (1994). Irregularity and locking to the seasonal cycle in an ENSO prediction model as explained by the quasi-periodicity route to chaos. *J. Atmos. Sci.*, *52*, 293–306.

Zebiak, S. E. and Cane, M. A. (1987). A model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, *115*, 2262–2278.

M.A. Cane and A.C. Clement, Lamont-Doherty Earth Observatory, Columbia University, P.O. Box 1000, Palisades, NY 10964-8000. (e-mail: mcane@ldeo.columbia.edu; clement@ldeo.columbia.edu)