A Role for the Tropical Pacific

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PERSPECTIVES: CLIMATE CHANGE

A Role for the Tropical Pacific

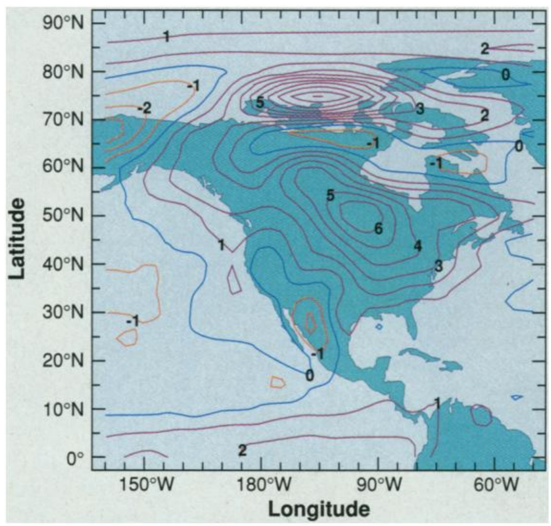
Mark A. Cane

Why are there ice ages? By 1980, the CLIMAP group (*1*) and other researchers had assembled a compelling case that paleoclimate variations are paced by Earth's orbital variations. The question was sharpened to "how do the orbital variations provoke such large responses"? The tropics were an unlikely place to find the answer. In the CLIMAP reconstruction of global sea surface temperature, tropical temperatures at the last glacial maximum hardly differed from their present values. The largest changes were found in the North Atlantic, typically 10°C and more. Furthermore, the North Atlantic is the "source" of the global ocean "conveyor" circulation. Changes in the North Atlantic will change the deep water that makes up most of the global ocean. The North Atlantic was the center of paleoclimate attention.

In the last two decades, new data (*2*) has shown climate changes with millennial time scales and no obvious orbital pacing. As Stocker discusses in his accompanying Perspective on page 61, these changes, which can be as abrupt as decades, are global in extent and typically close in timing if not synchronous (*3*). It is notable that they have been found in many parts of the tropics (*4*), where the weight of evidence now indicates a cooling of 3° to 5°C during the last glacial maximum. There are new questions: Why are the changes abrupt? What drives the nonorbital cycles?

The first answers were once again centered in the North Atlantic and its conveyor circulation (*3*, *5*), but the feeling is now growing that these new facts lead elsewhere (*2*, *6*). A telling point comes from the same model calculations cited in support of a major role for the conveyor (*7*). When the conveyor is shut down and the North Atlantic sea surface temperature is cooled in these models, which include pathways through the atmosphere as well as the ocean, there is a strong impact in the areas adjacent to and downstream of the North Atlantic but virtually no temperature change in the tropics or most of the rest of the globe. The models may be flawed, but these particular results are consistent with the many data studies of the North Atlantic Oscillation (*8*), the principal mode of climate variability in the modern record of the North Atlantic.

We now audition the tropical Pacific for the lead role in producing both orbital (forced) and millennial (internal) climate cycles. The idea is that unstable ocean-atmosphere interactions in the tropical Pacific, sometimes influenced by orbital variations and sometimes not, change tropical Pacific sea surface temperature distributions. The locus of atmospheric convection, which tends to lie over the warmest water in the tropics, changes simultaneously. Moving the convection changes the teleconnection pattern—the impacts on distant locations (*9*). The El Niño–Southern Oscillation (ENSO) cycle is the most familiar instance of instabilities in the tropical Pacific region that ultimately alter the global climate. In the warm phase (El Niño), the warmest waters move eastward to the vicinity of the date line; in the cold phase (La Niña), they contract at the west, around Indonesia. The global consequences (see figure), which are largely propagated through the atmosphere, follow within months at most. They are effectively instantaneous and simultaneous relative to paleoclimatic changes.



El Niño effects. Temperature anomalies over North America, averaged from December 1997 to February 1998, during the recent El Niño event.

SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

The physical links in this chain of effects are not particular to ENSO; they should hold at all longer time periods (*10*). Moreover, because of its sensitivity to the seasonal cycle in the tropics (*11*, *12*), we expect ENSO to be influenced by orbital variations, especially precessional changes. The same physical links also imply that the mean state of the tropical ocean and atmosphere will change (*10*). In a test of these ideas (*13*), an ENSO model (*11*) was run for 150,000 years. In response to imposed orbital variations in solar heating, the calculation shows increases or decreases in the frequency of ENSO warm or cold events and changes in their average amplitudes. Along with such variations go changes in the mean position of the warmest sea surface temperatures. The changes in temperature, which take less than 1000 years, are more abrupt than the orbital variations, although not so abrupt as the changes observed in the Greenland ice core (*14*).

Surprisingly, this run of the model has larger amplitude variations at millennial time scales than would be expected just from random fluctuations of the ENSO cycle (*15*). This excess power arises from nonlinear interactions within the model system, not from external causes: The millennial power is even more impressive in a 150,000-year run with no orbital forcing.

Even granting that millennial and orbitally paced variations can originate in the coupled tropical Pacific Ocean and atmosphere and that these can induce global changes, it does not follow that the global impacts reinforce to yield major temperature fluctuations. To warm (or cool), the planet demands a decrease (or increase) in snow, ice, and cloud albedo or an increase (or decrease) in longwave radiation trapping due to greenhouse gases or cloud. I argue that long-time behaviors will be analogous to those observed during the interannual ENSO cycle and that the warm (or cold) phase of ENSO results in planetary heating (or cooling).

The warm (El Niño) phase provides the richest data sets. It is well established that El Niño years are warmer in the mean. The figure illustrates one 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 (*14*). In El Niño years, the ice goes out early; we extrapolate, perhaps outrageously, to the idea that moving the convection to the central Pacific will help to

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melt the Laurentide Ice Sheet, while keeping it in the far western Pacific will favor ice sheet growth.

Satellite-based cloud climatologies show a tendency toward less low cloud during warm events, when the tropical area covered by cold waters is at a minimum. Low cloud has a net cooling effect because it reflects solar radiation but has little net effect on outgoing longwave radiation. There is also some evidence for an increase in atmospheric water vapor during warm events (*16*). These changes are small amplitude, but they all line up in the right sense for El Niño–like states to favor interglacial conditions and La Niña–like states to favor glacial conditions. Only atmospheric CO_2, which decreases during El Niño events in the modern record, is out of line.

The scenario sketched out here does not address the crucial issue of how the rest of the world will feed back on the tropical Pacific (*17*). It is very far from a comprehensive attempt to fit the existing paleoclimate record to a tropical Pacific perspective. There is clearly much modeling work and observational analysis to be done with the data in hand. Most paleoclimate data come from higher latitudes, however, and the records of the tropics in general and the Pacific in particular badly need to be enhanced.

It is premature to grant the tropical Pacific the lead role in explaining the expanded repertory of paleoclimate cycles. The weaknesses in the hypothesis are too serious, although arguably no worse than other contenders. However, now that it has been clearly established that these cycles are global, our understanding of modern climate suggests that the tropical Pacific must at the least be a featured player. Even at this early stage, the perspective presented here points in a new direction for paleomodeling and observational studies, one signposted by ideas of modern climate variability (*18*).

References and Notes

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17. B. Soden, *J. Clim.* **10**, 1050 (1997).
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PERSPECTIVES: CLIMATE CHANGE

The Seesaw Effect

Thomas F. Stocker

Abrupt shifts in climatic conditions at high latitudes in the Northern Hemisphere have captured the attention of climate scientists and the public since their discovery in terrestrial and marine records (*1*). When evidence from Greenland ice cores (*2*) and ocean models (*3*) converged in the mid-1980s, it became clear that these events can happen within a few years to decades, with effects that are at least hemispheric in extent (*4*). Recent modeling studies have further indicated that the dynamic behavior of the distant past may repeat itself in the future (*5*), and it is, therefore, of paramount importance to find out what determines rapid and millennial-scale climatic change.

There were 24 abrupt climate shifts (called Dansgaard/Oeschger events) during the last glacial period (*6*). The 16 events between 25,000 and 60,000 years ago occurred on average every 2000 years. The recurrence time scales for these events are highly variable. On the other hand, one notices a striking similarity in the Greenland ice record between individual events: The warming is abrupt and completed within a few years to decades, whereas the cooling is slower and takes at least a few centuries (*7*). Any theory of millennial-scale events must quantitatively explain this apparent asymmetry.

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Paleoclimatic records are based on the analysis of ice cores from northern and southern polar ice sheets, marine and lacustrian sediments, pollen profiles, and tree rings. Indicators complementary to the paleorecords allow us to identify the underlying mechanisms. Such indicators include (i) geographical patterns of events and their phase relationship; (ii) biogeochemical signals, such as changes in atmospheric greenhouse gases CO_2 and CH_4 and signals in their isotopic composition, particularly ^{13}C and ^{14}C; (iii) concomitant changes in the ocean and the distribution of tracers; and (iv) amplitudes, rates, and patterns of millennial-scale change as simulated by coupled physical-biogeochemical models. One of the pressing questions is where the centers of activity responsible for these abrupt and millennial-scale climate changes are located. The region of the high northern latitudes, especially the North Atlantic, has been the classic focus of this research. However, it may be argued that the first institutions of paleoclimatic research have been located around the North Atlantic, and a certain bias cannot be excluded. More recently, the focus has moved away from the North Atlantic to consider the influence of other regions on global climatic change.

A simple mechanical analog suggests some possibilities of how the climate system operates during such climatic swings. The system could react like a seesaw (*8*) to perturbations occurring in the north. In consequence, signals in the Southern Hemisphere would be of opposite sign (see panel A of figure). Alternatively, as Cane describes in his accompanying Perspective on page 59, the forcing could be located in the equatorial region rather than at high latitudes (*9*). In our mechanical analogy, this would correspond to a shift of the support point of the seesaw (panel B of figure). By comparing paleoclimatic records from only the high latitudes, we would be unable to distinguish these two cases from each other. A third possibility exists in which the equatorial regions drive changes in both hemispheres synchronously (panel C of figure).

The distinction of in-phase versus antiphase in the context of millennial cli-