El Niño's tropical climate and teleconnections as a blueprint for pre-Ice-Age climates

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At about 2.7 million years ago (Ma) the warm equable climates of early and middle Pliocene time (5-2.7 Ma) were replaced by recurring ice ages. Most attempts to explain the change appeal either to changes in CO_2 in the atmosphere or to reduced heat transport by the Atlantic Ocean. The sources of the strongest teleconnections in the current climate, however, lie in the tropics, and such connections occur by transport of heat and moisture by the atmosphere. The most prominent of these teleconnections link aberrations in sea surface temperatures in the equatorial Pacific, ENSO variations, with warm and dry or cool and wet variations in extratropical climates. We show that early and middle Pliocene climates, both in equatorial regions and in the extratropics, differ from present-day climates, in most cases, with the same spatial pattern as that associated with ENSO. A virtually permanent El Niño-like state appears to have characterized pre-Ice-Age climates, suggesting that transport of heat by the atmosphere was the principal mechanism that maintained extratropical warmth.

Imagine a world whose climate resembled that of a typical El Niño event (1) (Fig. 1). Canada would be warmer. Ice on the Great Lakes would be thinner (2). The area surrounding the Gulf of Mexico would be cooler and wetter than is usual at present, as would southeastern South America be. In contrast, India, northeastern South America near the mouth of the Amazon, and northeastern Australia would all be drier than they commonly are today, while East Africa would be wetter. Finally, the large temperature difference between the western tropical Pacific Ocean "warm pool" and the eastern Pacific "cold tongue" would be suppressed, if not absent. We show below that most of these conditions characterize pre-Ice-Age climates, at least in the period from 5 to 3 Ma, and probably a few million years earlier.

Although few would doubt that early to middle Pliocene global climate differed markedly from those since ~2.7 Ma (3), ruling out proposed explanations for the change has met with less unanimity. Some have supposed that CO_2 in the atmosphere has decreased and that the reduced greenhouse effect would then have cooled the globe sufficiently for ice sheets to grow (4,5). Recent estimates of partial pressures of CO_2 in past atmospheres, however, show only modest changes during the last 50 Myr (5,6). Others have suggested that heat transport associated with thermohaline circulation in the Atlantic was greater before the onset of continental ice sheets (5,7), and some suppose that the closing of the Isthmus of Panama at approximately the same time as global cooling effected a marked change in the thermohaline circulation. General circulation model calculations for an open and a closed isthmus, however, suggest that with an open isthmus ocean heat transport in the Atlantic would be less than with a closed isthmus (8).

Recently, we proposed that the closing of the Indonesian Seaway, with New Guinea approaching the equator and with much of Halmahera emerging in the last 5 million years, affected climates of the Pacific and Indian Oceans more than the closing of the Panamanian isthmus did (9). When further south, New Guinea did not block the warm water above the thermocline in the southern Pacific as it does now, allowing that warm water to pass into the Indian Ocean. Drawing on the importance of a warm central Indian Ocean for East African rainfall in the modern climate (10), we argued that the replacement of warm South Pacific water by colder water from the North

Pacific caused the Pliocene aridification of East Africa. Moreover, by blocking the warm southern Pacific water, New Guinea's steady northward movement would have provided the barrier against which the warm water blown westward by the present-day Walker circulation collects to form the "warm pool." The early to middle Pliocene temperature structure of the equatorial Pacific should have been more zonally uniform than it normally is today, and more like the modern Pacific in an El Niño state. If this is correct, we should expect early to middle Pliocene climates to resemble the pattern observed during El Niño (Fig. 1). We test that expectation here.

While we expect a resemblance to the modern El Niño pattern, a perfect reproduction is unlikely. In the modern record even “well known” El Niño teleconnections are absent in many individual events (1). When these absences are due to competing random influences, we expect the tropical teleconnections to prevail in a perpetual El Niño state. When the absences are due to systematic differences in some other aspect of the climate system (11), then we hardly know what to expect, for Pliocene atmospheric circulation surely did not match present-day circulation exactly.

Early to Middle Pliocene climate of the equatorial Pacific

In the present-day climate, sea surface temperatures (SSTs) of the western Pacific annually range from 3°C to 8°C higher than those of the eastern Pacific, and the thermocline is more than 100 m deeper in the west than in the east. Steady easterly winds over the central Pacific Ocean, driven by the zonal differences in SST, maintain these gradients. During El Niño, however, easterly winds over the tropical Pacific weaken; warm water from the warm pool moves eastward; and SSTs of the central and eastern Pacific approach those of the western Pacific (Fig. 1) (12). If pre-Ice-Age climates resembled those of El Niño, early to middle Pliocene temperatures near the surface of the western Pacific would have been slightly cooler than at present, and the thermocline should not have been as deep as it is today. Correspondingly, in the eastern Pacific, temperatures should have been higher than at present and the thermocline deeper.

Oxygen isotopic ratios, $\delta^{18}O$, measured from planktonic foraminifers from the western Pacific both in early Miocene time (13) and early Pliocene time (14,15) differ little from Pleistocene or present-day ratios. Prentice et al. (15) showed that $\delta^{18}O$ from organisms deposited between 4 and

5 Ma are 0.75$^{o}/_{oo}$ more positive than those for Holocene time, suggesting lower temperatures and/or saltier waters than at present. Moreover, maximum values of $\delta^{18}O$ between 4 and 5 Ma are comparable to those during glacial maxima, and minimum values are never lower than those of all of Pleistocene time (14,15). Because before ~3 Ma ice sheets, whose formation depletes the ocean of ^{16}O and hence enriches it in ^{18}O, were absent in the northern hemisphere except in Greenland, and because Antarctica is unlikely to have stored more ice then than it does now, late Miocene and early Pliocene water in the western Pacific must have been either cooler or more saline than it is today (13-15). Both lower temperatures and less rainfall leading to higher salinity characterize El Niño events of the present day.

Cannariato and Ravelo (16) took this a step further by comparing $\delta^{18}O$ measured from tests of the same species of surface dwelling foraminifer, *G. sacculifer,* since 5 Ma from sites in both the eastern and western equatorial Pacific (Fig. 2). They found that $\delta^{18}O$ in the east, in fact, was smaller than that in the west between ~5 and 4 Ma, suggesting that surface waters of the eastern Pacific may have been the warmer, ignoring likely differences in salinity.

Studies of the thermocline also suggest a different state before 3-4 Ma. Chaisson and Leckie (17) distinguished micro-organisms living at three depths: those near the surface, intermediate dwellers who spend most of their life cycles along the thermocline, and rare deep dwellers who live at the base of the thermocline. The plants that these organisms eat depend on light for photosynthesis, and the photic zone where sufficient light penetrates clear water is confined to depths shallower than ~100 m. Having noted, "Surface dwellers dominate the sediment assemblages of the lower and middle Miocene," they (17) inferred a shoaling of the thermocline in the western Pacific in middle Miocene time (~12 Ma), when "a consequent expansion of niche space for intermediate-water dwellers" occurred. In the late Miocene-early Pliocene, the ratio of thermocline-dwelling species to those in the mixed layer was 60%-40%, which implies that the thermocline lay near if not within the photic zone (Fig. 2). Then during mid-Pliocene time, thermocline-dwelling species in the western Pacific dropped to 40%, leaving 60% in the mixed layer and suggesting a deepening of the thermocline (18). After ~2.6 Ma, assuming a revised time scale (19), the asymmetry increased to 20%-80% thermocline to mixed-layer dwellers. Chaisson (18) inferred a thickening of the mixed layer in the western Pacific so that species living in the thermocline were pushed below the photic zone (Fig. 2). In the eastern Pacific, differences in $\delta^{18}O$ measured in the surface dwelling *G. sacculifer* and the deeper dwelling *N. dutertrei* or *G. Tumida* have diverged since 4.2 Ma (Fig. 2), suggesting that the latter have lived in increasingly cooler water and hence that the thermocline has shoaled in that area (14).

El Niño events are notorious for a weakening of the easterly tradewinds over the equatorial central Pacific, where SSTs reach maximum values, evaporation is high, and convection in the atmosphere occurs; the easterlies in some El Niño events even reverse direction over the western Pacific (20). Less widely appreciated is a corresponding strengthening of the easterlies over the eastern Pacific (21). Consistent with an El Niño-like climate, aeolian deposits over the eastern equatorial Pacific suggest stronger winds there in late Miocene and early to mid-Pliocene time than later (22). Grain sizes of such deposits were higher before ~4 Ma than after, and stronger winds are necessary to transport larger grains (23).

The deep thermocline that characterizes the present western Pacific Ocean is maintained by the winds associated with the normal Walker circulation, which is in essence a weak La Niña state. Thus, as global cooling occurred in the Pliocene, deepening of the thermocline in the western Pacific, cooling of surface water in the eastern Pacific (Fig. 2), and weakening of easterly trade winds in the east all concur with a change from a state more like El Niño in late Miocene and early Pliocene time to one more like La Niña by the late Pliocene.

Middle Pliocene climate of extratropical regions

An early Pliocene climate in the tropical Pacific resembling that of El Niño does not guarantee that climates in the rest of the world would resemble those during El Niño. In carrying the teleconnection signals globally, the planetary waves generated in the tropical Pacific are guided by mean atmospheric winds. Pliocene atmospheric circulation surely differed from that at present. Moreover, aspects of the remote influences are sensitive to the pattern of SST anomalies in the tropical Pacific (24), and although the Pliocene ocean was similar to an El Niño state, it was not identical. Nevertheless, we test the working hypothesis that the Pliocene world looked much like a modern El Niño state.

One of the most robust teleconnections associated with El Niño is a warmer high-latitude North America, extending from Alaska across much of Canada (1). Warming of this area during El Niño is largely a winter phenomenon. Ice is much less well developed over the Great Lakes in El Niño winters than in normal years (2). An obvious sign of a warmer climate in Miocene and early Pliocene time is the absence of continental ice sheets, which seem to have developed at ~2.7 Ma in Canada and Fennoscandia (25). Moreover, Wolfe (26) inferred from fossil leaf assemblages that mean annual temperatures in the Alaska Range, now -3˚C, were above freezing at 5.9 Ma. Ager (26) drew similar conclusions from Pliocene pollen and spore assemblages north of the Alaska Range, in eastern Alaska, and in the Yukon. Similarly, ostracodes, foraminifera, and pollen assemblages (27) from along the east coast of North America north (but not south) of 35˚N indicate higher temperatures in middle Pliocene time than now (Fig. 1).

Although most of the earth was warmer in early to middle Pliocene time than since that time, one consistent exception is the area that includes northern Mexico and surrounds the Gulf of Mexico, where temperatures also are lower and precipitation higher during El Niño, particularly in winter, than normal (Fig. 1) (1). Using present-day habitats of ostracodes to assign paleoenvironments to fossil taxa, Cronin and Dowsett (27) inferred lower Pliocene temperatures in Florida and South Carolina than at present. Pollen from Florida also suggest cooler early Pliocene climates in western Florida than today (27). From a middle Pliocene fossil assemblage near Veracruz, Mexico, in the southwest corner of the Gulf of Mexico, abundant spruce (*Picea*), but also other flora, suggest an "annual mean temperature 2-3˚C lower and rainfall slightly greater than at present" (28). Finally, from fossils of a tortoise, turtles, and alligators, Thompson (29) inferred that 3.2 Ma at Beck Ranch in the middle of Texas the climate was wetter than at present, if winters were mild. All of these inferences concur with early to middle Pliocene climates being similar to those during El Niño events.

Warm winters in Alaska and Canada and cool, wet winters in the area near the Gulf of Mexico are predictable consequences of perturbations to atmospheric circulation in the tropics (1). Perturbations to SSTs in the tropics are much more effective in inducing teleconnections to more distant localities than are perturbations are higher latitudes (30). Particularly in boreal winter, when the jet stream is strong and perturbed by high terrain and continent-ocean differences, the high SSTs and low-level convergence over the tropical central Pacific perturb the basic state of the atmosphere in the Northern Hemisphere in a predictable way. A background state consisting of a strong jet stream deflected from zonal symmetry by a stationary wave pattern determines where upper level high- and low-pressure centers lie. Tropical forcing in the central Pacific perturbs the jet-stream so as to amplify, or weaken, these high- and low-pressure centers.

Readers might question our utilizing perturbations to a present-day basic state dominated by a strong jet-stream to justify a warmer Pliocene climate in North America, when the basic state in Pliocene time should have been different. The principle contributors to the standing wave pattern of the jet-stream, however, differed little from today; the movement of continents and their margins and changes in elevation of the high terrain of Asia and North America have been minor. Thus, although we cannot predict the magnitudes of differences between Pliocene and present-day climates by assuming a permanent El Niño-like state, we should not be surprised that the spatial pattern of these differences over North America are similar.

Another teleconnection in western North America, though less consistent than those discussed above, merits attention. Higher than normal rainfall often occurs in spring, summer, and autumn of El Niño years in the Great Basin (Fig. 1) (1,31). The flooding in Salt Lake City in 1983 provides a spectacular example. Inferences of Pliocene climates also indicate wetter conditions at ~3 Ma than at present (32). Modern habitats of fossil lacustrine ostracodes and fish in paleo-lakes and pollen from southwest Idaho, and from central Arizona in the case of ostracodes, imply wetter environments between 4.5 and 2.8 Ma than at present (33). Both the chemistry of spring and lake deposits and the mere existence of widespread lakes throughout much of the Great Basin in middle Pliocene time (29,32,34) also imply a wetter climate than at present.

Approximately symmetrically disposed across the equator from the Gulf of Mexico region, southeastern South America (Northeast Argentine, Uruguay, and southwest Brazil) also receives more rain during El Niño events (Fig. 1) during the Boreal winter than in normal seasons (1). Correspondingly, Zarate and Fasana (35) reported that vertebrate fossils imply warmer and wetter Pliocene (and early Pleistocene) climates than since that time.

Some, but not all, compilations of teleconnections also call for a warmer Japan during El Niño (1), and evidence for Pliocene climates is also ambiguous. Pollen, sampled both from on land and from ODP sites offshore (36), contain taxa no longer found in Japan, but thriving in warmer parts of China. Data from marine environments, however, do not show the early middle Pliocene ocean near Japan to have been warmer than now, but either similar or even cooler (37). The marine measurements could reflect a cooler climate, or they could be a consequence of a change in the position of the warm, northward-flowing Kuroshio Current off the east coast of Japan.

India typically receives less rain during El Niño years than in normal times (1) (Fig. 1), though in some eras, such as the past few decades, this relationship fails (11). The reasons for this failure are not known, but it has been suggested that warmer temperatures and less snow cover over Eurasia shift the Walker circulation to the southeast (11). In any case, India apparently was not as dry in Pliocene time as it is today. Gaur and Chopra (38) reported that in early to middle Pliocene time wooded grassland with bushland or just grassland indicate a warm, humid climate in northern India just south of the Himalaya. These habitats then gave way to dominantly grassland associated with a relatively arid and less warm climate at approximately the time of the Gauss/Matuyama boundary, now dated at 2.6 Ma (19). Less detailed reports from both Kashmir and the Kathmandu valley of Nepal concur with cooling and drying since mid-Pliocene time (38).

The most consistently observed and most robustly correlated extratropical teleconnections associated with El Niño describe a global pattern of climatic anomalies that resemble the differences between Pliocene and present-day climates, but not without exceptions (Fig. 1).

Middle Pliocene climate of tropical regions outside the Pacific

One of the most robust correlations with El Niño is a drying over northeastern South America (1). During El Niño the eastern region of subsidence of the Walker circulation is displaced eastward over northeastern South America. Northeastern Australia also becomes more arid during El Niño, as the region of heavy rain near New Guinea is displaced eastward. Less well correlated with El Niño are heavy rains over eastern Africa (Fig. 1).

Accumulation rates of aeolian deposits depend most on the aridity of the source area, not on wind strength (23), and Hovan (22) showed that accumulation rates of aeolian deposits at four sites from 3-4˚S to 6-7˚N at ~112˚W in the eastern Pacific have decreased since ~4 Ma. The source area surely lies in northern South America including the Amazon basin, for at this latitude easterly winds would have transported sediment. As Hovan (22) recognized, this decrease in accumulation rates indicates a change from more arid to wetter conditions in northern South America, consistent with the climate there before ~4 Ma being more like that of El Niño than the present.

Northeastern Australia, like most of the continent, seems to have been more humid in early Pliocene time than in Quaternary time. From the evolution of both plants and animals, Archer et al. (39) reported that aridity began to increase in late Miocene time (6-8 Ma), though the "first 'arid' mammals came at 3.9 Ma and grazers at 3-4 Ma," and that grasslands have expanded since 3.4 Ma. Similarly, Bowler (39) wrote that although progressive desiccation was well advanced by ~2.5 Ma, the main imprint is Quaternary. The pattern of Pliocene climate change seen in Australia is, if not opposite to, very different from that associated with El Niño (though there are few paleoclimatic data from the part of Australia affected consistently by modern El Niño). Australia thus stands with India as the important exceptions to the El Niño pattern of the Pliocene (Fig. 1). In this context it is interesting to note that during the unusually strong El Niño of 1997-98, the Indian monsoon rainfall was normal and Australian rainfall nearly so.

Heavy rains frequently fall on East Africa in association with El Niño events, but sometimes not, and some El Niño events have little effect there (1,40). Correspondingly, eastern Africa was more humid in early Pliocene time (41). We attribute the aridification of east Africa only indirectly to a change from an El Niño-like Pacific climate to its present state, with the direct link being with the Indian Ocean (9).

Implications of the El Niño-pre-Ice-Age similarity

If the northward movement of New Guinea with respect to the equator, and the emergence of much of Halmahera since 5 Ma blocked warm water in the upper ocean of the Pacific south of the equator, the upper part of the Indian Ocean would cool (9,42). Exploiting the effects of warm or cold central Indian Ocean SSTs on modern East African rainfall (10), we argued that such a blocking of warm Pacific water accounts for the aridification of eastern Africa since ~ 4-5 Ma. The blocking of warm water should also have effected increased temperatures in the upper part of the western Pacific (42), and hence encouraged, if not created, the present-day zonal asymmetry of SSTs. The difference between tropical Pacific climates in Pliocene time from those at present offers one test of such a suggestion. As discussed above, in early Pliocene time, the surface water in the western Pacific appears to have been both cooler than at present (or more saline) and cooler than in the east (14-18). Moreover, the thermocline in the west appears to have been shallower than at present, and that in the east deeper, such that little or no east-west gradient existed.

Because when the asymmetry of Pacific SSTs breaks down during El Niño, much of the globe experiences aberrant temperatures and rainfall, a further test of New Guinea's and Halmahera's role can be made by comparing the teleconnections of El Niño as a blueprint for Pliocene climates outside the equatorial Pacific. The evidence summarized above shows that El Niño's teleconnections match the differences between Pliocene and present-day climates in most areas where robust teleconnections have been recognized. The comparisons, of course, are far from ideal for all the reasons that make paleoclimatology difficult. Dates in many cases are poorly determined, and we have been somewhat cavalier in lumping together observations applying to different times between 6 and ~ 2.7 Ma. As usual, inferences of temperature or precipitation from comparisons of paleontological assemblages with modern-day analogs are sufficiently uncertain that quantifying uncertainties is difficult, and sometimes not done at all.

Insofar as Pliocene climates resemble those during El Niño (Fig. 1), presumably the processes that make warm areas warmer than normal and cool areas cooler also operate. Lindzen (43) has long argued that warming at high latitudes depends as much on heat transport from the tropics via a strengthened Hadley cell, as on the usual explanations of increased CO_2 or ocean heat transport. Indeed, the Hadley circulation is strengthened during El Niño (44), and heat is transported from tropics to mid-latitudes more efficiently than during more normal times (45). The suggestion that El Niño and its teleconnections provide a blueprint not only for Pliocene climates but also for the mechanisms responsible for them is not without flaws. First, in many parts of the world where El Niño's teleconnections are weak, Pliocene climates were quite different from those at present. Parts of Europe and the Mediterranean region, for instance, were warmer than they are now, but El Niño's teleconnections to these areas seem to be weak. Second, enhanced heat transport from the tropics during the El Niño phase of the ENSO cycle is perpetuated by the tropical Pacific Ocean's recharging its heat reservoir during the period since the last El Niño (46). Nevertheless, applied to Pliocene time, a strengthened Hadley circulation associated with El Niño calls attention to the possibility that Pliocene cooling leading to the Ice Ages occurred because of decreased atmospheric heat transport from the tropics (9). In view of all the reasons why Pliocene climates should not resemble El Niño tropical climates and teleconnections, the match is perhaps better than we might expect, given that teleconnections result from perturbations to a basic state, and in Pliocene time, the basic state must have been different.

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Figure captions

Figure 1. Plots of summer and winter temperature and rainfall anomalies during El Niño (from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm.gif), with Pliocene paleoclimate observations, which we discuss in the text, labeled for the various regions.

Figure 2. Evidence greater zonal symmetry of sea-surface temperatures and depths of the thermocline than exists today in the equatorial pacific. (a) Time series of oxygen isotopes measured in planktonic foraminifers from the eastern and western Pacific since 5 Ma (16). Note the larger values of $\delta^{18}O$ for the eastern Pacific today, consistent with lower temperatures there, but smaller values before ~4 Ma, suggesting that at that time the SST in the east was greater than that in the west. (b) Time series of percentages of surface dwelling and thermocline dwelling microorganisms since ~7 Ma in the western Pacific (14). Note that near 4 Ma, surface dwellers become a large fraction and thermocline dwellers eventually nearly disappear, suggesting a deepening of the thermocline well below the photic zone. (c) Time series of differences in oxygen isotopes between those of the surface dwelling *G. sacculifer* and the deeper dwelling *N. dutertrei* or *G. Tumida* (14). The differences measure the temperature gradients across the mixed layer (upper 100-200 m) of the eastern and western Pacific Ocean. They show that before ~4 Ma, the gradients in both the east and west were gentle, but since ~4 Ma, that in the east has been steep, consistent with a shallower thermocline there.