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

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[1] At ~2.7 million years ago the warm equable climates of early and "middle" Pliocene time (used here to mean from ~5 to ~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 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, El Niño-Southern Oscillation (ENSO) variations, with warm and dry or cool and wet anomalies in extratropical climates. We show that in most cases early and middle Pliocene climate both in equatorial regions and in the extratropics differ from present-day climates with the same spatial pattern as that associated with ENSO. For instance, not only was Canada warmer during early Pliocene time than at present, as it is during El Niño, but the region surrounding the Gulf of Mexico appears to have been cooler and a bit wetter, as it commonly is during El Niño. 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. Accordingly, cooling and the growth of recurring ice sheets in the Northern Hemisphere resulted from the development of a strong Walker circulation and a weakening of the Hadley circulation. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3309 Meterology and Atmospheric Dynamics: Climatology (1620); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4522 Oceanography: Physical: El Niño; *KEYWORDS:* ice age, El Niño, teleconnections, atmospheric heat transport

1. Introduction

[2] Imagine a world whose climate resembled that of a typical El Niño event (Figure 1) [e.g., *Halpert and Ropelewski*, 1992; *Mason and Goddard*, 2001; *Rasmusson and Carpenter*, 1982; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998]. Canada would be warmer and drier. Ice on the Great Lakes in winter would be thinner [*Assel*, 1998]. The area surrounding the Gulf of Mexico would be cooler and wetter than is usual at present, as would southeastern South America. 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 for a few million years earlier.

[3] Although few would doubt that early to middle Pliocene (~5–2.7 Ma) global climate differed from that since ~2.7 Ma [e.g., *Dowsett et al.*, 1994, 1996, 1999; *Thompson and Fleming*, 1996], 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 then cooled the globe sufficiently for ice sheets to grow [*Crowley*, 1991, 1996; *Raymo et al.*, 1996]. Recent estimates of partial pressures of CO_2 in the atmosphere of the past, however, show only modest changes during the past 50 Myr [*Pagani et al.*, 1999a, 1999b; *Pearson and Palmer*, 2000; *Raymo et al.*, 1996; *Van Der Burgh et al.*, 1993]. Others have suggested that heat transport associated with thermohaline circulation in the Atlantic was greater before the onset of continental ice sheets [*Dowsett et al.*, 1992; *Raymo et al.*, 1996; *Rind*, 1998; *Rind and Chandler*, 1991; *Sloan et al.*, 1996], 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 [*Maier-Reimer et al.*, 1990], and paleoceanographic proxies for deep flows appear to be consistent with a more vigorous Pliocene than present-day thermohaline circulation [*Ravelo and Andreasen*, 2000].

[4] 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, had more effect on the climates of the Pacific and Indian Oceans than did the closing of the Panamanian isthmus or changes in thermohaline circulation [*Cane and Molnar*, 2001]. When farther south, New Guinea did not block the warm water above the thermocline in the southern Pacific, as it does now, and thereby allowed 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 [*Goddard and Graham*, 1999], 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

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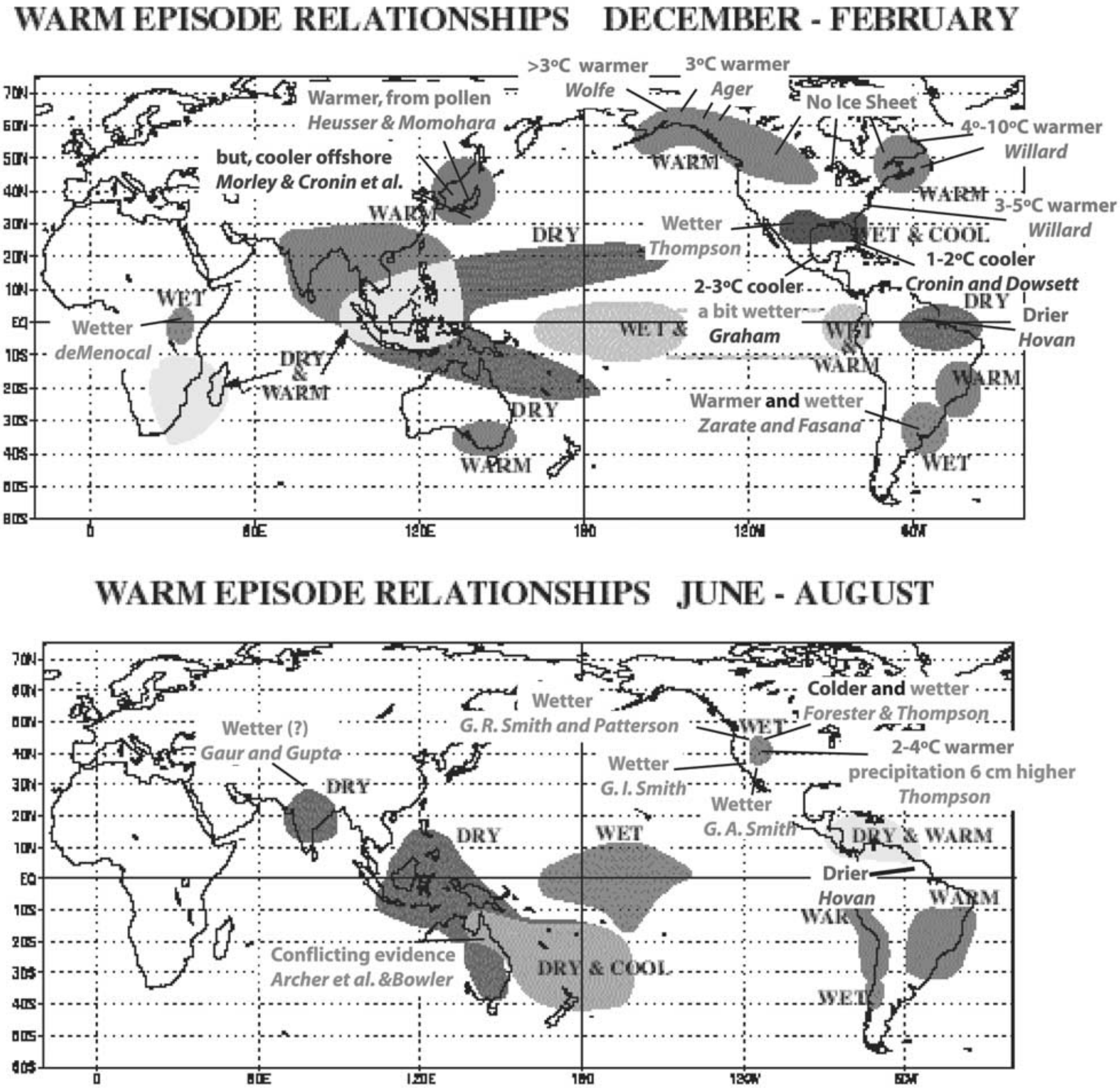


Figure 1. Plots of summer and winter temperature and rainfall anomalies during El Niño (adapted from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm.gif) with Pliocene paleoclimate observations, which we discuss in the text, labeled for the various regions. See color version of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

present-day Walker circulation collects to form the "warm pool" (Figure 2). 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 (Figure 2). If this is correct, we should expect early to middle Pliocene climates to resemble the pattern observed during El Niño (Figure 1). We test that expectation here.

[5] While we expect a resemblance of pre-Ice Age regional climates to the modern El Niño pattern, a perfect reproduction is unlikely. In the modern record, even "well-known" El Niño teleconnections are absent during many individual events [*Halpert and Ropelewski*, 1992; *Mason and Goddard*, 2001; *Rasmusson and Carpenter*, 1982; *Ropelewski and Halpert*, 1986, 1987, 1996; *Trenberth et al.*, 1998]. Where these absences result from competing random influences, we expect the tropical teleconnections to prevail in a perpetual El Niño state. Where the absences are due to systematic differences in some other aspect of the climate system [e.g., *Krishna Kumar et al.*, 1999; *Giannini et al.*, 2001], however, we cannot expect Pliocene atmospheric circulation to match anomalies in present-day circulation.

2. Early to Middle Pliocene Climate of the Equatorial Pacific

[6] In the present-day climate, sea surface temperatures (SSTs) of the western Pacific annually range from 3° to 8°C higher than those of the eastern Pacific, and the thermocline is >100 m deeper

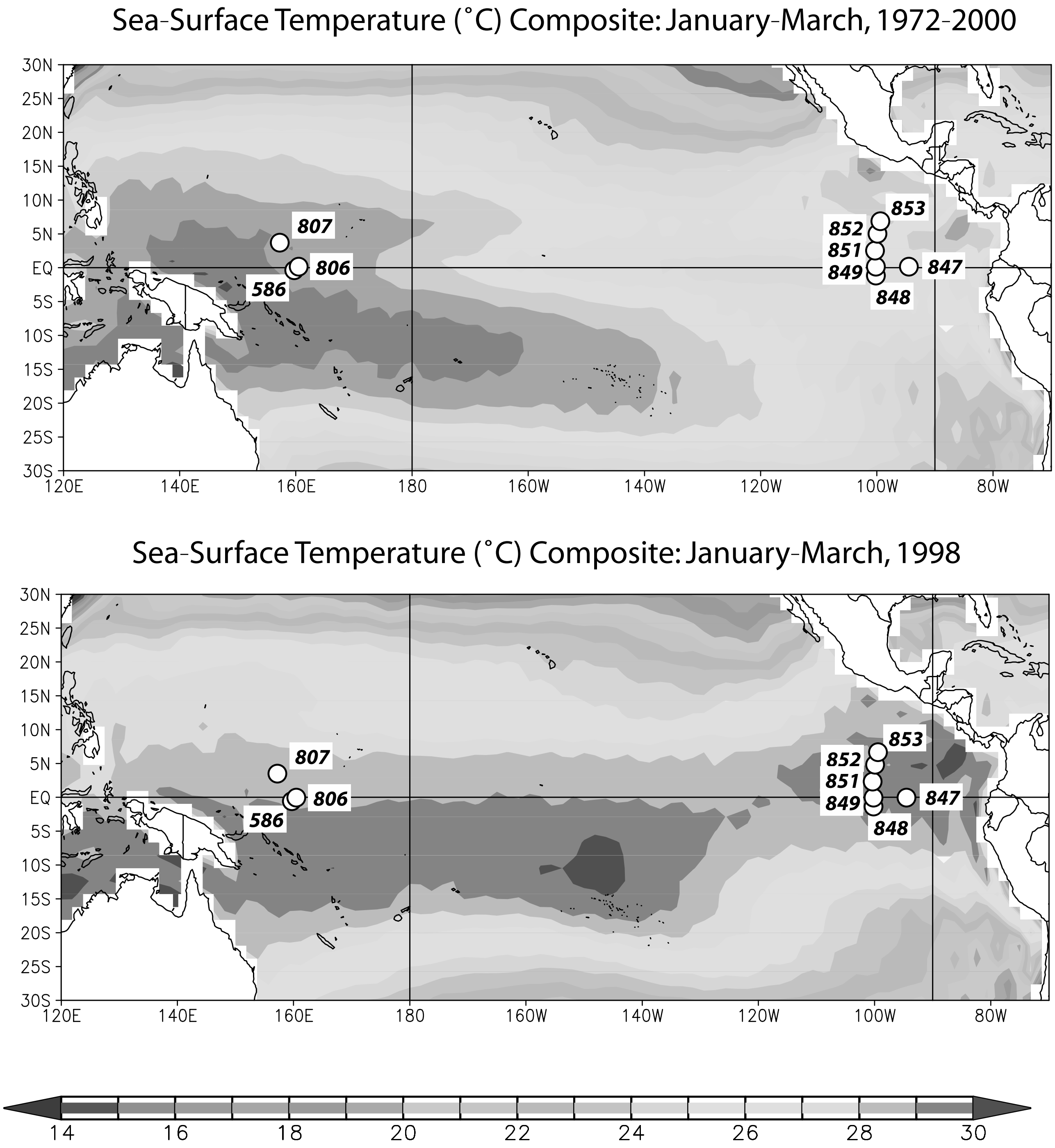


Figure 2. Sea surface temperatures and ODP sites from the equatorial Pacific. The top map shows mean winter (January–March) sea surface temperature for the period 1972–2000, and the bottom map shows the mean sea surface temperature (in °C) for January through March of the El Niño year 1998. In the El Niño year, high temperatures extend into the eastern Pacific, eliminating the climatological cold tongue. The image was obtained using the NCEP data [*Kalnay et al.*, 1996] provided by the NOAA CIRES Climate Diagnostics Center, Boulder, Colorado, on their web site at http://www.cdc.noaa.gov/. Site numbers beside the white circles indicate the locations of ODP sites used. See color version of this figure at back of this issue.

in the west than in the east [*Philander*, 1989]. 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 (Figure 2) [e.g., *Wallace et al.*, 1998]. 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 there should not have been as deep as it is today. Correspondingly, in the eastern Pacific, temperatures should have been higher, and the thermocline should have been deeper than at present.

[7] Oxygen isotopic ratios, $\delta^{18}O$, measured from planktonic foraminifera from the western Pacific both in early Miocene time [*Savin et al.*, 1985] and early Pliocene time [*Chaisson and Ravelo*, 2000; *Prentice et al.*, 1993; *Whitman and Berger*, 1992] differ little from Pleistocene or present-day ratios. *Prentice et al.* [1993] showed that $\delta^{18}O$ from organisms deposited between 4 and 5 Ma at Site 807 (Figure 2) are 0.75‰ more positive than those for Holocene time. Moreover, maximum values of $\delta^{18}O$ between 4 and 5 Ma, also from Deep Sea Drilling Program (DSDP) Site 586 and ODP Site 806, were comparable to those during glacial maxima, and minimum values were never lower than any of those in Pleistocene time [*Chaisson and Ravelo*, 2000; *Prentice et al.*, 1993; *Whitman and Berger*, 1992]. Because ice sheets, whose formation depletes the ocean of ^{16}O and hence enriches it in ^{18}O, were absent in the Northern Hemisphere before ~3 Ma 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 [*Chaisson and Ravelo*, 2000; *Prentice et al.*, 1993; *Savin et al.*, 1985]. Both lower temperatures and less rainfall, leading to higher salinity, characterize El Niño events of the present day.

[8] *Cannariato and Ravelo* [1997] took this a step further by comparing $\delta^{18}O$ measured from tests of the same species of surface-dwelling foraminifer, *Globigerinoides sacculifer*, deposited since 5 Ma at Sites 851 and 586 in the eastern and western equatorial Pacific (Figure 2). Their observation that $\delta^{18}O$ in the east was smaller than that in the west between ~5 and 4 Ma (Figure 3) suggests that surface waters of the eastern Pacific might have been the warmer, if we ignore likely differences in salinity. The similarity of their measurements of $\delta^{18}O$ from the eastern and western sites between 4 and 1.6 Ma might suggest that a cooling of the eastern Pacific neither coincided with the onset of Northern Hemisphere glaciation nor occurred gradually, as a strict application of the simple analogy between El Niño-Southern Oscillation (ENSO) and pre-Ice Age climates implies. It would be helpful to have additional tests of the change in equatorial Pacific climates since ~5 Ma based on other SST proxies, such as Mg/Ca.

[9] Studies of the thermocline also suggest a different state before 3–4 Ma. *Chaisson and Leckie* [1993] distinguished microorganisms 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 euphotic 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 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 at Site 806 (Figure 2) was ~60–40% [*Chaisson*, 1995], which implies that the thermocline lay near if not within the euphotic zone (Figure 3). Then during mid-Pliocene time, thermocline-dwelling species in the western Pacific gradually dropped to ~40%, leaving ~60% in the mixed layer, and by ~2.6 Ma, assuming a revised timescale [*Berggren et al.*, 1995], the asymmetry had increased to ~20% thermocline to 80% mixed layer dwellers. *Chaisson* [1995] inferred a gradual deepening of the thermocline in the western Pacific, so that by 2.6 Ma most species living in the thermocline were pushed below the euphotic zone.

[10] *Chaisson and Ravelo* [2000] inferred a corresponding shoaling of the thermocline in the eastern Pacific. They found that differences in $\delta^{18}O$ measured in the surface-dwelling *G. sacculifer* and deeper-dwelling *Neogloboquadrina dutertrei* or *G. Tumida* at Site 847 (Figure 2) diverged since 4.2 Ma (Figure 3), from which they inferred that the latter have lived in increasingly cooler water and hence that the thermocline in the eastern Pacific has shoaled. The abrupt change at 4.2 Ma is less consistent with a gradual blockage of warm water south of the equator by New Guinea and Halmahera than a more gradual change in $\delta^{18}O$ differences over the period from 5 to 2.6 Ma would be. If further evidence corroborates such a rapid change, it will call into question our hypothesis that New Guinea’s northward movement and Halmahera’s emergence gradually changed the equatorial Pacific waters.

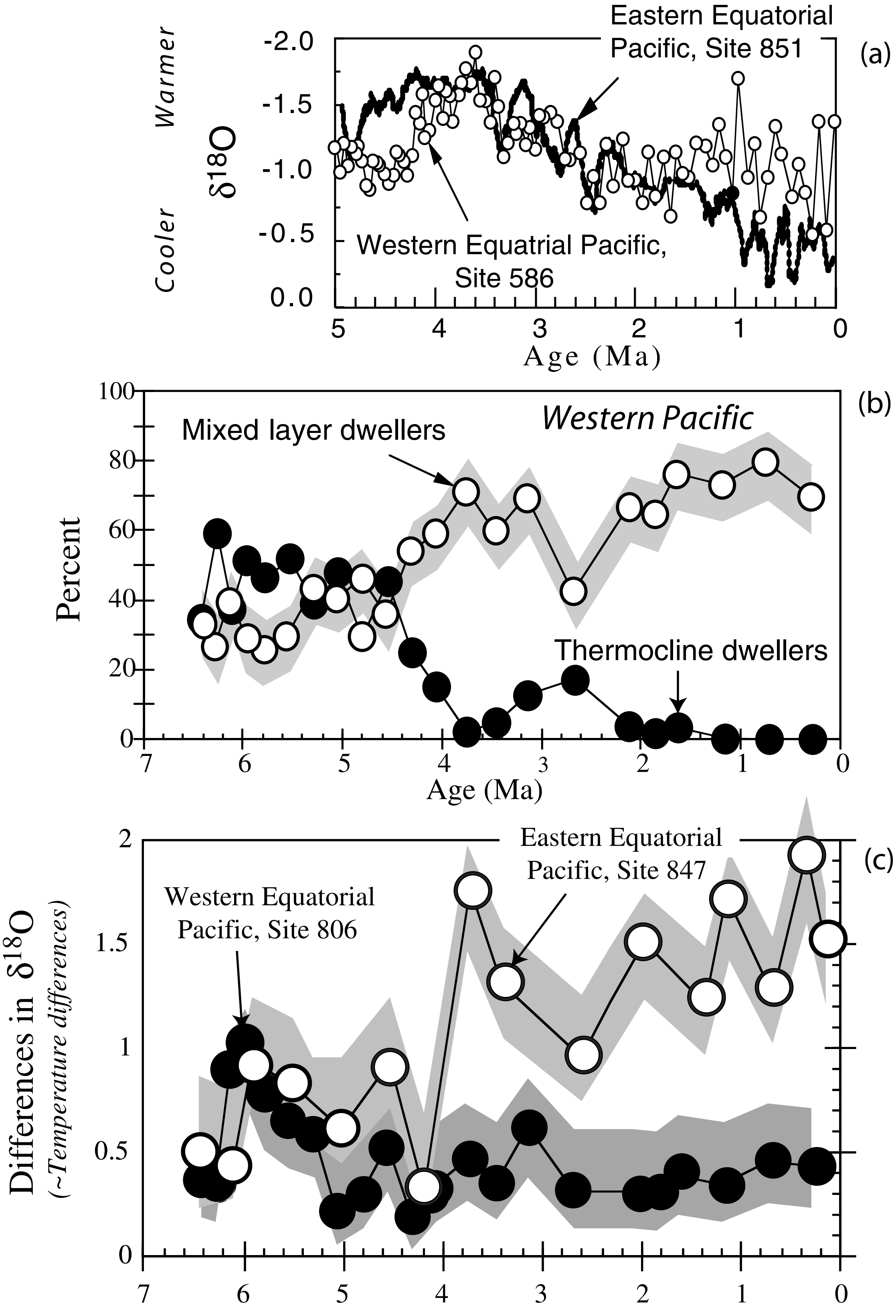
[11] El Niño events are noteworthy for a weakening of the easterly trade winds over the equatorial central Pacific, where SSTs reach maximum values, evaporation is high, and convection in the atmosphere occurs; the easterlies in some El Niño events even reverse direction over the western Pacific [e.g., *McPhaden and Picaut*, 1990]. Less widely appreciated is a corresponding strengthening of the easterlies over the eastern Pacific during El Niño [*Harrison and Larkin*, 1998]. 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 [*Hovan*, 1995]. Grain sizes of such deposits were higher before ~3–4 Ma than after, and stronger winds are necessary to transport larger grains [e.g., *Rea*, 1994].

[12] Winds associated with the normal Walker circulation, which is in essence a weak La Niña state, maintain the deep thermocline that characterizes the present western Pacific Ocean. Thus, as global cooling occurred in the Pliocene, the deepening of the thermocline in the western Pacific [*Chaisson*, 1995; *Chaisson and Leckie*, 1993], cooling of surface water in the eastern Pacific (Figure 3) [*Chaisson and Ravelo*, 2000; *Cannariato and Ravelo*, 1997], and weakening of easterly trade winds in the east [*Hovan*, 1995] 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.

3. Middle Pliocene Climate of Extratropical Regions

[13] An early Pliocene climate in the tropical Pacific resembling that of El Niño does not guarantee that regional climates in the rest of the world would resemble those during El Niño. In carrying the teleconnection signals globally, planetary waves generated in the tropical Pacific are guided by mean atmospheric winds, and aspects of the remote influences are sensitive to the pattern of SST anomalies in the tropical Pacific [e.g., *Hoerling and Kumar*, 2000; *Hoerling et al.*, 2001; *Kumar and Hoerling*, 1997; *Yin and Battisti*, 2001]. Pliocene atmospheric circulation, however, surely differed from that at present, and although the early Pliocene tropical ocean appears to have been similar to that during an El Niño state, surely they also were not identical. Nevertheless, we test the working hypothesis that the Pliocene regional climates bore resemblances to those of the modern El Niño state.

[14] One of the most robust teleconnections associated with El Niño is a warmer high-latitude North America, extending from Alaska across much of Canada (Figure 1) [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1986; *Trenberth et al.*, 1998]. Warming and drying [*Shabbar et al.*, 1997] of this area during El Niño are largely winter phenomena. Ice is thinner over the Great


Eastern Equatorial Pacific, Site 851
(a)
Warmer
Cooler
δ18O
-2.0
-1.5
-1.0
-0.5
0.0
Western Equatrial Pacific, Site 586
5
4
3
2
1
0
Age (Ma)
(b)
Western Pacific
Mixed layer dwellers
Thermocline dwellers
Percent
100
80
60
40
20
0
7
6
5
4
3
2
1
0
Age (Ma)
(c)
Eastern Equatorial Pacific, Site 847
Western Equatorial Pacific, Site 806
Differences in δ18O
(~Temperature differences)
2
1.5
1
0.5
0
7
6
5
4
3
2
1
0
Age (Ma)

Lakes in El Niño winters than in normal years [*Assel*, 1998]. An obvious sign of a warmer climate in late Miocene and early Pliocene time is the absence of continental ice sheets, which developed at ~2.7 Ma in Canada and Fennoscandia [*Haug et al.*, 1999; *Shackleton et al.*, 1984], according to the revised timescale of *Berggren et al.* [1995]. Moreover, *Wolfe* [1994] inferred from fossil leaf assemblages that mean annual temperatures in the Alaska Range, now −3°C, were above freezing at 5.9 Ma. *Ager* [1994] drew similar conclusions from Pliocene pollen and spore assemblages north of the Alaska Range, in eastern Alaska, and in the Yukon. Similarly, ostracods [*Cronin*, 1991; *Cronin and Dowsett*, 1990, 1996, *Willard et al.*, 1993], foraminifera [*Dowsett and Poore*, 1990, 1991; *Dowsett and Wiggs*, 1992], and pollen assemblages [*Groot*, 1991; *Willard*, 1994] from along the east coast of North America north (but not south) of 35°N imply middle Pliocene (~3.5–3 Ma) temperatures that were several degrees higher than those now (Figure 1).

[15] 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 are lower and precipitation higher than normal during El Niño, particularly in winter (Figure 1) [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1986, 1987, 1996; *Trenberth et al.*, 1998]. Using present-day habitats of ostracodes to assign paleoenvironments to fossil taxa, *Cronin and Dowsett* [1990, 1996; *Cronin*, 1991] inferred lower Pliocene temperatures in Florida and South Carolina than at present. Pollen from Florida also suggests cooler early Pliocene climates in western Florida than today [*Willard et al.*, 1993]. From a middle Pliocene fossil assemblage near Veracruz, Mexico, in the southwest corner of the Gulf of Mexico, which includes abundant spruce (*Picea*) among other flora, *Graham* [1989a, 1989b] deduced an "annual mean temperature 2°–3°C lower and rainfall slightly greater than at present." Moreover, T. M. Cronin (personal communication, 2001) infers a warming of shallow water in the southwestern Gulf of Mexico near Veracruz since middle Pliocene time, from the similarity of the sequence of Pliocene ostracods reported by *Machain-Castillo* [1986] to those he studied from Florida and South Carolina [*Cronin*, 1991; *Cronin and Dowsett*, 1990, 1996]. Finally, from fossils of a tortoise, turtles, and alligators, *Thompson* [1991] reported that at Beck Ranch in the middle of Texas, the climate was wetter at 3.2 Ma than at present, if winters were mild. All of these inferences concur with early to middle Pliocene climates differing from those in subsequent times in the same sense that El Niño teleconnections differ from average present-day climates.

[16] Warm winters in Alaska and Canada and cool, wet winters in the area near the Gulf of Mexico are predictable consequences of tropical perturbations to atmospheric circulation. Perturbations to SSTs in the tropics are much more effective in inducing teleconnections to more distant localities than are perturbations at higher latitudes [*Hoskins and Karoly*, 1981; *Lau and Nath*, 1994; *Webster*, 1981]. Particularly in boreal winter, when the subtropical jet is strong and its path is shaped 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 subtropical jet 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 subtropical jet so as to amplify, or weaken, these high- and low-pressure centers.

[17] Readers might question our utilizing perturbations to a present-day basic state dominated by a strong subtropical jet to justify a warmer Pliocene climate in North America, when the basic state in Pliocene time should have been different. The principal contributors to the standing wave pattern of the subtropical jet, however, differed little from today; movements 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.

[18] 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 (Figure 1) [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1986; *Lall and Mann*, 1995; *Trenberth et al.*, 1998]. 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 [e.g., *Forester*, 1991]. Modern habitats of fossil lacustrine ostracodes and fish in paleolakes from southwest Idaho and central Arizona [*Smith and Patterson*, 1994] and pollen from southwest Idaho [*Thompson*, 1996] imply wetter environments between 4.5 and 2.8 Ma than at present. 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 [*Forester*, 1991; *Hay et al.*, 1986; *Smith*, 1994; *Smith et al.*, 1993; *Smith*, 1984; *Thompson*, 1991] imply a wetter climate than at present.

[19] Southeastern South America (northeast Argentina, Uruguay, and southwest Brazil) also receives more rain during El Niño events during the boreal winter than in normal years (Figure 1) [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998]. Correspondingly, *Zarate and Fasana* [1989] reported that vertebrate fossils imply warmer and wetter Pliocene (and early Pleistocene) climates than since that time.

[20] Some, but not all, compilations of teleconnections call for a warmer Japan during El Niño [e.g., *Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998], and evidence constraining Pliocene climates is also ambiguous. Pollen, sampled both on land and from ODP sites offshore [*Heusser and Morley*, 1996; *Momohara*, 1994], contains taxa no longer found in Japan but that thrive today in warmer parts of China. Data from marine environments, however, do not show the middle Pliocene

Figure 3. (opposite) Evidence of greater zonal symmetry of sea surface temperatures and depths of the thermocline in early Pliocene time than exist today in the equatorial Pacific. (a) Time series of oxygen isotopes measured in planktonic foraminifers from the eastern and western Pacific since 5 Ma [*Cannariato and Ravelo*, 1997]. Note the larger values of δ^{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 may have been 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 [*Chaisson and Ravelo*, 2000]. Note that near 4 Ma, surface dwellers became a large fraction and thermocline dwellers eventually nearly disappeared, suggesting a deepening of the thermocline well below the euphotic 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* [*Chaisson and Ravelo*, 2000]. Variations in these differences with time reflect changes in temperature gradients across the upper 100–200 m of the eastern and western Pacific Ocean. 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.

ocean near Japan to have been warmer than now but either similar or even cooler. On the basis of mollusks, diatoms, and ostracodes that lived between 3.4 and 2.3 Ma, *Cronin et al.* [1994] reported relatively warmer water adjacent to Japan between 3.4 and 2.7 Ma followed by a cooling trend after 2.7 Ma, but their inferred temperatures in the warmer period were no higher than those today. Using radiolaria, *Heusser and Morley* [1996] reported cooler water than today throughout the period between 4.8 and 2.8 Ma, with only very brief warm periods that almost look like aberrations in their time series. 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. From variations in surface temperatures inferred from alkenones, *Sawada and Handa* [1998] suggested that the strength and path of this current has varied during the past 25 kyr. As Japan lies just west of where the warm, northward flowing Kuroshio and cold, southward flowing Oyashio Currents mix [e.g., *Talley et al.*, 1995], a shift in the strength of one or the other will affect surface temperature of the water east of Japan.

[21] India apparently was not as dry in Pliocene time as it is today. *Gaur and Chopra* [1984] 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 but cooler climate at approximately the time of the Gauss/Matuyama boundary, now dated at 2.6 Ma [*Berggren et al.*, 1995]. Less detailed reports from both Kashmir and the Kathmandu valley of Nepal concur with cooling and drying since mid-Pliocene time [*Agrawal*, 1988; *Igarashi et al.*, 1988].

[22] As India typically receives less rain during El Niño years than in normal times [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998] (Figure 1), the inferred Pliocene climate provides an exception to the pattern that we suggest. In some eras, such as the past two decades, however, the relationship of low rainfall during El Niño years fails [*Krishna Kumar et al.*, 1999]. The reasons for this failure are not known, but *Krishna Kumar et al.* [1999] offered two possible explanations. In general, during El Niño, when the locus of convection and the rising branch of the Walker circulation moves eastward over the central Pacific, the western subsiding branch of the Walker circulation also moves eastward to overlie India and brings dry air to the subcontinent [e.g., *Webster et al.*, 1998]. Higher temperature and less snow cover over Eurasia in recent years may have pushed the subsiding branch to the southeast and thus reduced the effect of the Walker circulation on Indian climate. Alternatively, a greater eastward shift of the rising branch of the Walker circulation over the central or even eastern Pacific during El Niño events since ~1980 might have drawn the subsiding branch eastward from India, again reducing its effect over India. *Krishna Kumar et al.* [1999] showed that the loci of maximum and minimum velocity potential at 200 mbar during El Niño events since 1980 lie east of those during El Niño events of the preceding 30 years.

[23] Had we used teleconnections associated with El Niño only since ~1980, the pattern would fit Pliocene India. In any case, 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 (Figure 1).

4. Middle Pliocene Climate of Tropical Continental Regions

[24] One of the most robust correlations with El Niño is a drying over northeastern South America (Figure 1) [*Halpert and Ropelewski*, 1992; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998]. During El Niño the eastern subsiding limb of the Walker circulation is displaced eastward over northeastern South America. Northeastern Australia also becomes more arid during El Niño years [e.g., *McBride and Nicholls*, 1983], as the region of heavy rain near New Guinea is displaced eastward. Less well correlated with El Niño are heavy rains over eastern Africa (Figure 1).

[25] Accumulation rates of aeolian deposits depend most on the aridity of the source area not on wind strength [e.g., *Rea*, 1994], and *Hovan* [1995] showed that accumulation rates of aeolian deposits at four sites in the eastern Pacific (Sites 848, 849, 852, and 853 in Figure 2) 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* [1995] recognized, this decrease in accumulation rates indicates a change from more arid to wetter conditions in northern South America, consistent with an El Niño-like climate there before ~4 Ma.

[26] Northeastern Australia, like most of the continent, seems to have been more humid in early Pliocene than Quaternary time. From the evolution of both plants and animals, *Archer et al.* [1995] 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." Grasslands have expanded since 3.4 Ma. Similarly, *Bowler* [1976] wrote that although progressive desiccation was well advanced by ~2.5 Ma, its 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 most strongly affected by El Niño). Australia thus stands with India as the important exceptions to the El Niño-like pattern of the Pliocene (Figure 1). In this context it is interesting to note that during the unusually strong El Niño of 1997–1998, not only was the Indian monsoon rainfall normal but Australian rainfall was nearly so.

[27] Heavy rains frequently fall on East Africa in association with El Niño events, but sometimes they are not in association, and some El Niño events have little effect there [*Halpert and Ropelewski*, 1992; *Indeje et al.*, 2000; *Nicholson and Kim*, 1997; *Ogallo*, 1989; *Ropelewski and Halpert*, 1987, 1996; *Trenberth et al.*, 1998]. Correspondingly, as summarized elsewhere [e.g., *Cane and Molnar*, 2001; *deMenocal*, 1995], eastern Africa was more humid in early Pliocene time. We [*Cane and Molnar*, 2001] attributed 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. We suggested that warm water from the Pacific dominated the Indonesian Throughflow into the Indian Ocean and that warm water led to higher precipitation over East Africa than later, when colder water of the North Pacific provided the source of Indonesian Throughflow. In the modern climate, warm central Indian Ocean temperatures correlate with heavy rain over East Africa [*Goddard and Graham*, 1999].

[28] From the localized evolution of one foraminifer, *Srinivasan and Sinha* [1998, 2000] suggested that the Indonesian Seaway closed around 5 Ma. Before 5.6 Ma, planktonic foraminifera in the Pacific and Indian Oceans had been similar. Between 5.6 and 4.2 Ma, however, *Pulleniatina spectabilis* evolved and lived only in the equatorial Pacific; it has not been found in Indian Ocean samples. As other foraminifera have continued to live in both oceans, the relationship of this one taxon to the closing of the seaway, if suggestive, must remain tentative.

[29] At present, we are aware of only *Shackleton and Hall*'s [1990] $\delta^{18}O$ record from the planktonic foraminifer *G. sacculifer* from the equatorial Indian Ocean (~4°S, 66.5°E) as offering a possible test of the proposed warming of the Indian Ocean. Their measured decrease in $\delta^{18}O$ from 4.5 to 3.2 Ma suggests a warming and/or freshening of the surface water, contrary to the change that we suggest for Indonesian Throughflow water that flows west

across the Indian Ocean at ∼10°S. We anticipate that additional paleoceanographic studies of microorganisms deposited in the Indian Ocean will provide a more definitive test of such a switch from a warm to a cold Indonesian Throughflow.

5. Implications of the El Niño pre-Ice Age Similarity

[30] The blocking of warm water by New Guinea and Halmahera should also have effected increased temperatures in the upper part of the western Pacific [*Rodgers et al.*, 2000] 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) [*Chaisson*, 1995; *Chaisson and Leckie*, 1993; *Chaisson and Ravelo*, 2000; *Prentice et al.*, 1993] and possibly cooler than in the east [*Cannariato and Ravelo*, 1997]. Moreover, the thermocline in the west appears to have been shallower than at present, and that in the east appears to have been deeper, such that little or no east-west gradient existed.

[31] These paleoceanographic changes are coeval with the closing of the Isthmus of Panama, and we cannot disprove any contribution by that closure. We are aware of neither obvious reasons for nor general circulation model runs [e.g., *Maier-Reimer et al.*, 1991] showing effects that this closing would have on tropical Pacific surface waters.

[32] 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 with 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. Finally, we have ignored the abrupt changes in some records, such as the rapid shift in $\delta^{18}O$ shown in Figure 3c, but clearly, if abrupt changes characterize most records, our suggestion of a gradual switch in sources of Indonesian Throughflow between 5 and ∼2.5 Ma and concurrent gradual changes in the structure of the equatorial Pacific Ocean would seem unlikely.

[33] Insofar as Pliocene climates resemble those during El Niño (Figure 1), presumably the processes that make warm areas warmer than normal and cool areas cooler during El Niño events also operated then. *Lindzen and Hou* [1988; *Hou,* 1993, 1998; *Hou and Lindzen,* 1992; *Lindzen,* 1994] have 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 [*Oort and Yienger*, 1996], and heat is transported from the tropics to midlatitudes more efficiently than during more normal times [*Sun*, 2000; *Sun and Trenberth*, 1998]. *Hou and Lindzen* [1992] argued that a stronger Hadley circulation could increase baroclinicity in the midlatitudes and thereby foster growth of baroclinic instability and transient eddies. Numerical experiments with a simplified, idealized general circulation model confirmed that a strengthened Hadley circulation could enhance heat transport in the extratropics by stimulating the growth of eddies and Rossby wave propagation [*Hou*, 1993, 1998; *Hou and Molod*, 1995]. The stronger Hadley circulation exports more angular momentum to midlatitudes, and that additional eastward velocity aloft increases the vertical wind shear below the subtropical jet [*Hou*, 1998]. As *Hou* [1993, 1998] stated, this vertical wind shear provides the energy source for the development of eddies, which transport heat to higher latitudes. Admitting an incomplete understanding of how a strengthened Hadley circulation effects more efficient eddy transport of heat to higher latitudes, *Hou* [1993] concluded, "If tropical convection has an important role in modulating the extratropical dynamic heat transport and temperatures, the past climate regimes may be understood in terms of convective heating patterns quite different from that observed in the present-day. Given this sensitivity, it is not implausible that tropical convection could modulate the efficiency of wave transport outside the tropics, thereby acting as a regulator of the equator-to-pole temperature contrast. . . ." We suggest that the expected stronger Hadley circulation in Pliocene time not only transferred more heat to midlatitudes but also enhanced the baroclinic eddy mechanism for transferring heat to higher latitudes. The additional heat was sufficient to prevent ice sheets from developing.

[34] The thermal structure of the present tropical Pacific Ocean does not sustain a perpetual El Niño. Enhanced heat transport from the tropics during the El Niño phase of the ENSO cycle is perpetuated by recharging the tropical Pacific Ocean's heat reservoir between El Niños [e.g., *Cane and Zebiak*, 1985; *Jin*, 1997; *Sun and Liu*, 1996; *Wyrtki*, 1985]. The air-sea interactions first hypothesized by *Bjerknes* [1969] could, in principle, sustain a perpetual warm state if the two fluids are very strongly coupled [*Cane et al.*, 1990]. Westerlies and a warm eastern Pacific Ocean would interact to maintain such a state. With a deep eastern thermocline the incoming solar flux would not have to heat upwelling cold waters from thermocline depth, as it does now. The solar heat could instead be used to warm the extratropics. *Dijkstra and Neelin* [1995] discussed such perpetual states in the context of flux errors in coupled general circulation models. Moreover, without the cold tongue, low-level stratus clouds should have been sparser than today, and hence a lower Pliocene than present-day albedo would have resulted [*Philander et al.*, 1996]. Finally, a warmer sea surface in the tropics, due to a significantly warmer eastern part despite a possibly cooler western part, should facilitate greater evaporation. If at least some of that additional water vapor remained in the atmosphere and did not precipitate out via the greenhouse effect, it would maintain higher surface temperatures. Higher surface temperatures would imply larger changes in convective heating in response to SST anomalies, enhancing the strength of the coupling between ocean and atmosphere.

[35] 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. 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 too feeble to account for the differences. These areas have strong relationships with the North Atlantic Oscillation, but there is little we can say about the state of the atmosphere over the North Atlantic in the Pliocene. Moreover, given the sensitivity of teleconnections to both the change in the location of convection in the tropics [e.g., *Hoerling et al.*, 2001; *Yin and Battisti*, 2001] and the state of the atmosphere, the El Niño "blueprint" is an insufficient plan for all of Pliocene climate.

[36] In light of the reasons why Pliocene climates should not resemble El Niño tropical climates and teleconnections, the match (Figure 1) is perhaps better than we might expect. The resemblance

is even closer if we use the teleconnection pattern of the past two decades only. (A deeper understanding of the particularities of the 1997–1998 event might shed light on Pliocene climate.) Moreover, the similarity of Pliocene climates with those during El Niño supports the contention that the tropics force climate more than other regions do, even on geologic timescales [e.g., *Cane*, 1998; *Hou*, 1993, 1998; *Hou and Lindzen*, 1992; *Lindzen*, 1994; *Lindzen and Hou*, 1988]. In particular, the 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 [*Cane and Molnar*, 2001].

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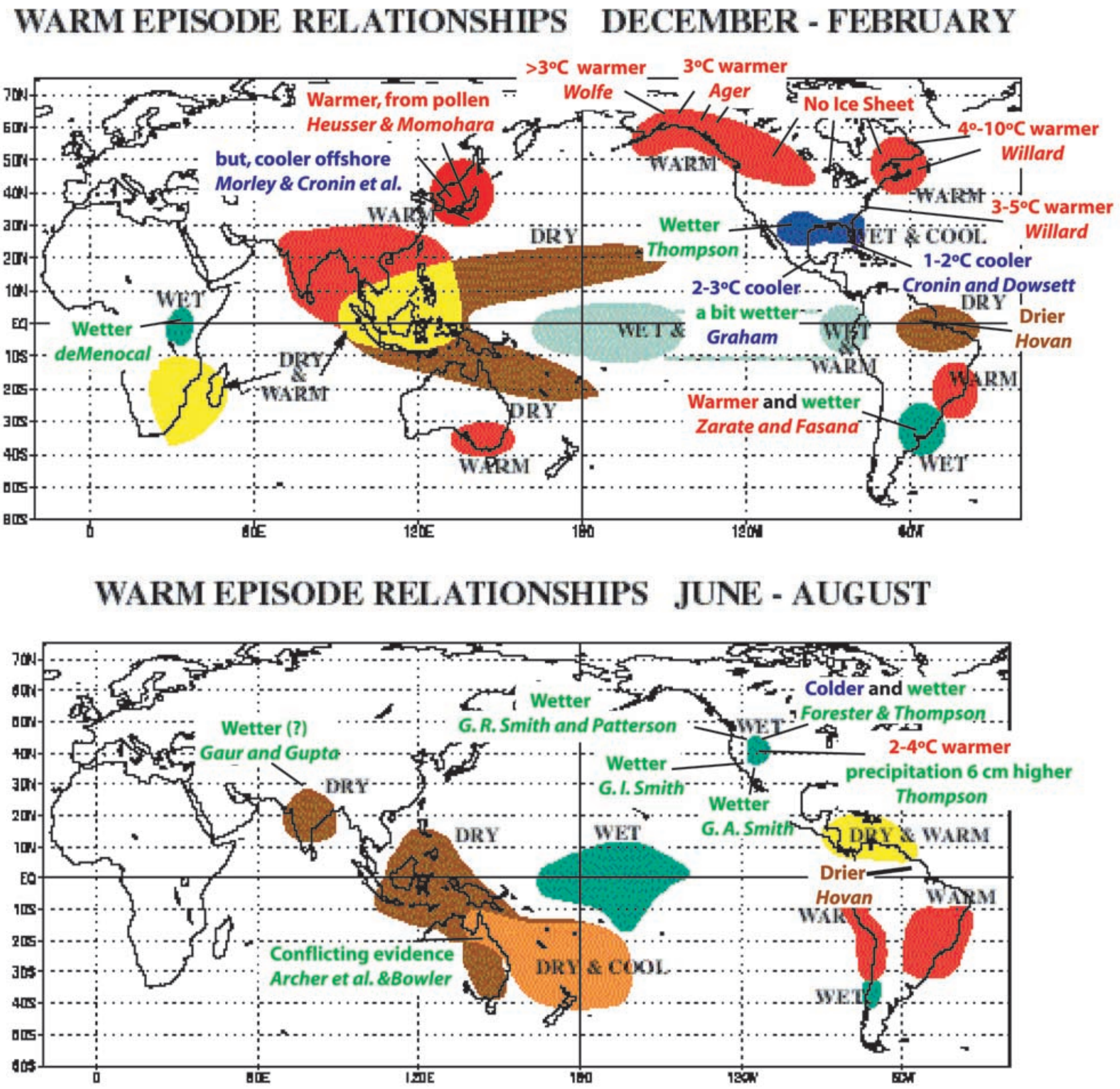
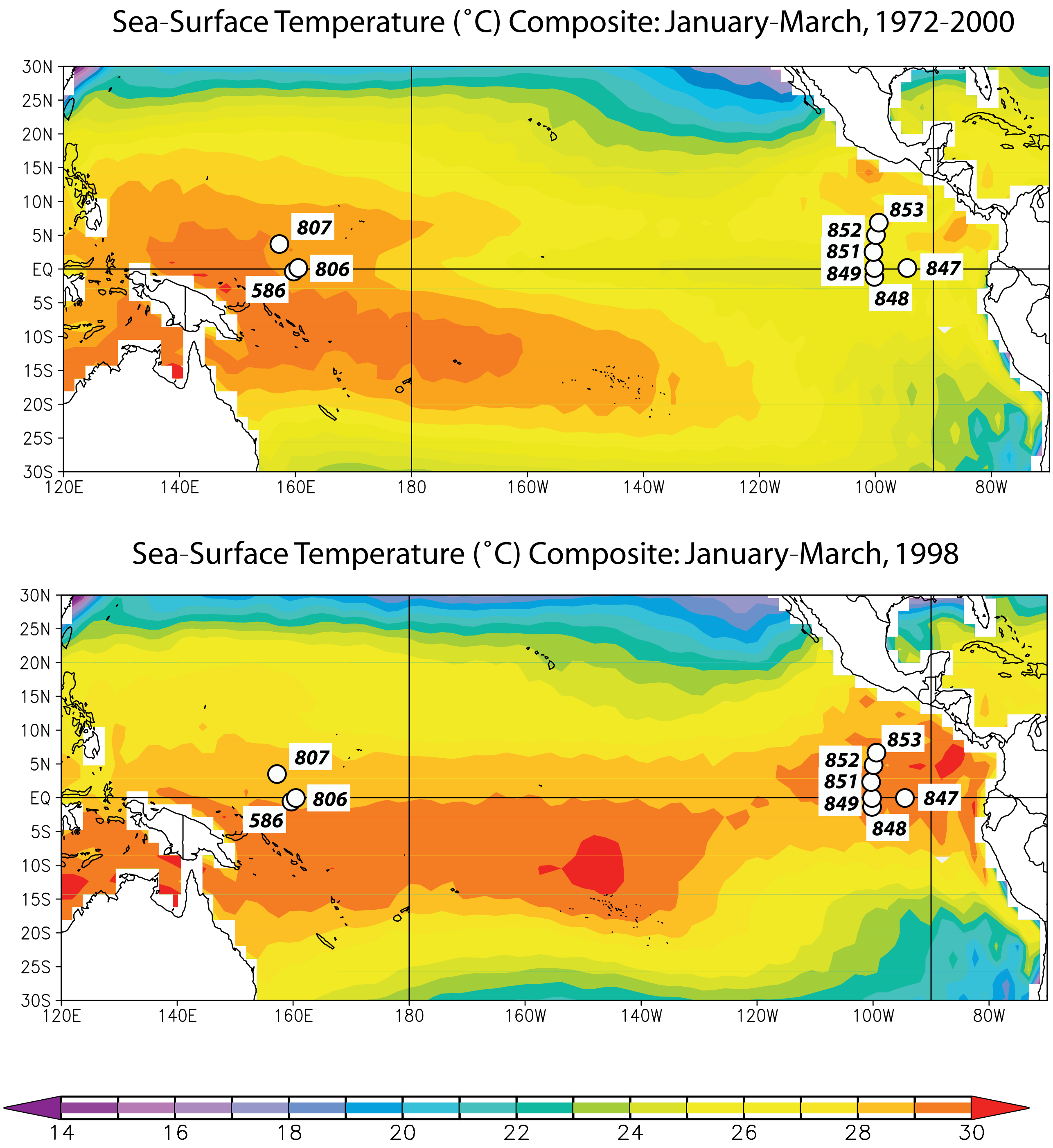


Figure 1. Plots of summer and winter temperature and rainfall anomalies during El Niño (adapted from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm.gif) with Pliocene paleoclimate observations, which we discuss in the text, labeled for the various regions.



Sea-Surface Temperature (˚C) Composite: January-March, 1972-2000

Sea-Surface Temperature (˚C) Composite: January-March, 1998

Figure 2. Sea surface temperatures and ODP sites from the equatorial Pacific. The top map shows mean winter (January–March) sea surface temperature for the period 1972–2000, and the bottom map shows the mean sea surface temperature (in °C) for January through March of the El Niño year 1998. In the El Niño year, high temperatures extend into the eastern Pacific, eliminating the climatological cold tongue. The image was obtained using the NCEP data [*Kalnay et al.*, 1996] provided by the NOAA CIRES Climate Diagnostics Center, Boulder, Colorado, on their web site at http://www.cdc.noaa.gov/. Site numbers beside the white circles indicate the locations of ODP sites used.