Early Pliocene (pre–Ice Age) El Niño–like global climate: Which El Niño?

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ABSTRACT

Paleoceanographic data from sites near the equator in the eastern and western Pacific Ocean show that sea-surface temperatures, and apparently also the depth and temperature distribution in the thermocline, have changed markedly over the past ~4 m.y., from those resembling an El Niño state before ice sheets formed in the Northern Hemisphere to the present-day marked contrast between the eastern and western tropical Pacific. In addition, differences between late Miocene to early Pliocene (pre–Ice Age) paleoclimates and present-day average climates, particularly in the Western Hemisphere, resemble those associated with teleconnections from El Niño events, consistent with the image of a permanent El Niño state. Agreement is imperfect in that many differences between early Pliocene and present-day climates of parts of Africa, Asia, and Australia do not resemble the anomalies associated with canonical El Niño teleconnections. The teleconnections associated with the largest El Niño event in the past 100 yr, that in 1997–1998, do, however, reveal similar patterns of warming and the same sense, if not magnitude, of precipitation anomalies shown by differences between late Miocene-early Pliocene paleoclimates and present-day mean climates in these regions. If less consistent than those for the 1997–1998 event, temperature and precipitation anomalies correlated with the Pacific Decadal Oscillation also mimic many differences between early Pliocene and present-day climates. These similarities suggest that the sea-surface temperature distribution in the Pacific Ocean before Ice Age time resembled most that of the 1997–1998 El Niño, with the warmest region extending into the easternmost Pacific Ocean, not near the dateline as occurs in most El Niño events. This inference is consistent with equatorial Pacific proxy data indicating that at most a small east-west gradient in sea-surface temperature seems to have existed along the equator in late Miocene to early Pliocene time. Accordingly, such a difference in sea-surface temperatures may account for the large global differences in climate that characterized the earth before ice sheets became frequent visitors to the Northern Hemisphere.

Keywords: paleoclimate, Ice Age, El Niño, Early Pliocene, paleoceanogrpahy

INTRODUCTION

Abundant evidence suggests that before ca. 3 Ma, before continental ice sheets frequented the Northern Hemisphere, the eastern equatorial Pacific Ocean was much warmer than today (Chaisson and Ravelo, 2000; Lawrence et al., 2006; Ravelo et al., 2004, 2006; Wara et al., 2005) with a small, and perhaps negligible, east-west gradient in sea-surface temperatures. Moreover, changes both in the fractions of surface, intermediate depth, and thermocline-dwelling microorganisms from the western Pacific and in oxygen isotopes recorded by them suggest that the thermocline there has deepened since 3–4 Ma (Chaisson, 1995; Chaisson and Leckie, 1993). These observations, plus similarities between extra-tropical early Pliocene climates and El Niño teleconnections, led to the suggestion of a permanent El Niño state in pre–Ice Age time (e.g., Fedorov et al., 2006; Molnar and Cane, 2002; Philander and Fedorov, 2003; Ravelo et al., 2006). This suggestion, in fact, grew in part from theoretical predictions for how the structure of the upper ocean and its circulation have changed over late Cenozoic time (e.g., Cane and Molnar, 2001; Philander and Fedorov, 2003). Not surprisingly, controversies continue to surround hypothesized stimuli for switches both from permanent El Niño to the present-day ENSO state and from ice-free Laurentide and Fenno-Scandinavian regions to the alternation between glacial and interglacial periods that has occurred since ca. 2.7 Ma.

As is well known in modern climatology, not only do El Niño events differ from one another, but also the sea-surface temperature (SST) distribution of the Pacific Decadal Oscillation (PDO) shares many features of that associated with El Niño events (e.g., Mantua et al., 1997; Zhang et al., 1997). Thus, whereas on the one hand, some form of SST distribution resembling a canonical El Niño, or Pacific Decadal Oscillation, seems to have characterized the pre–Ice Age equatorial Pacific SST distribution, the precise form has neither been defined well, nor predicted theoretically. Yet, differences in both the teleconnections associated with different El Niño events and with the Pacific Decadal Oscillation and in sensitivity studies carried out with atmospheric general circulation models (e.g., Barsugli and Sardeshmukh, 2002; Barsugli et al., 2006) demonstrate that the paleoclimate record might place constraints on the early Pliocene equatorial Pacific SST distribution. Toward that end, we synthesize evidence that constrains regional climates in that period.

During an El Niño event, warming of the sea surface is concentrated within a few degrees of the equator in the eastern half of the Pacific, but the longitude distribution varies markedly, depending at least in part on the strength of the event (Fig. 1). In this paper, we show anomalies

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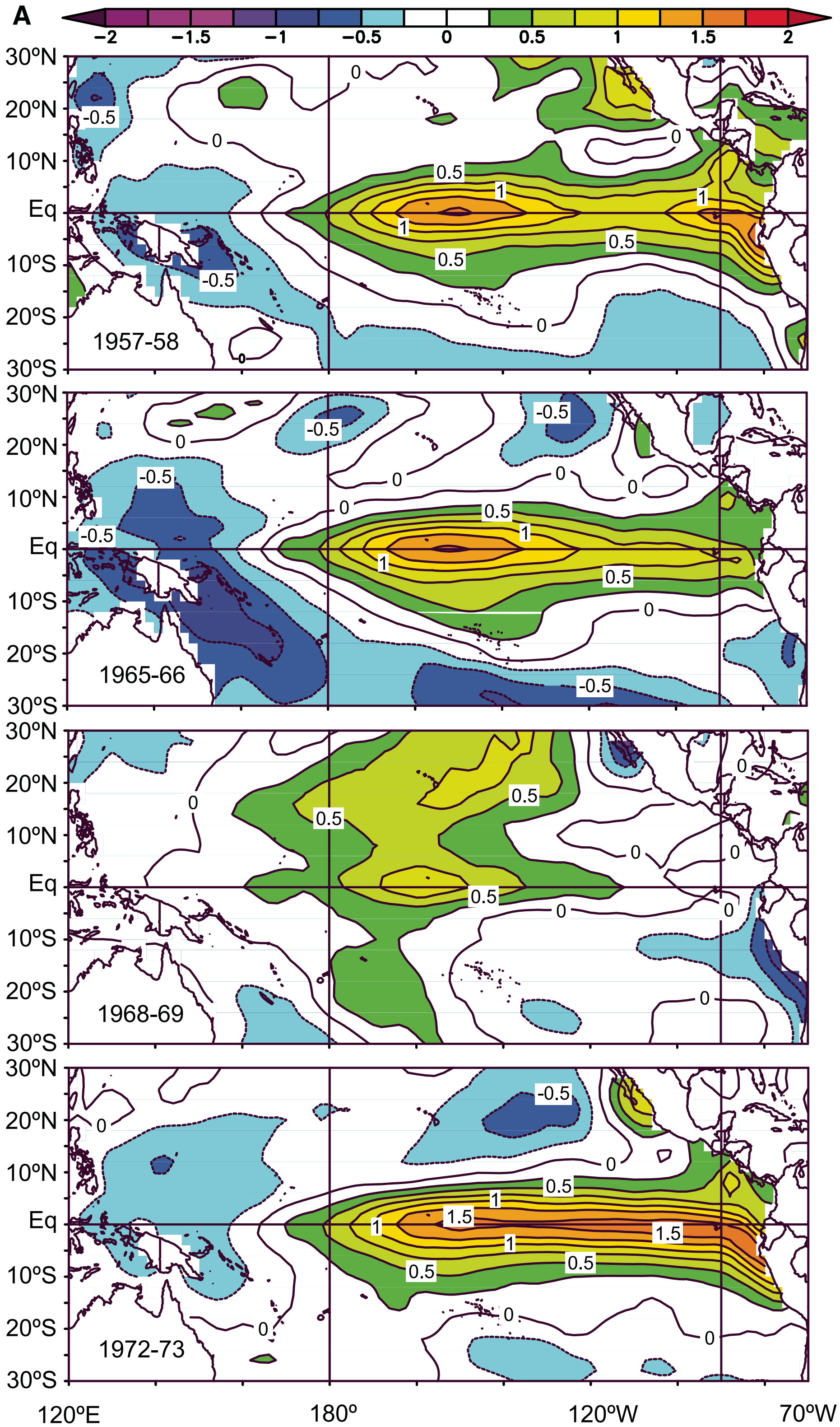


Figure 1 (*on this and following two pages*). Maps of equatorial Pacific Sea-Surface Temperatures (SST) anomalies for the nine major El Niño events since 1950 and for the Pacific Decadal Oscillation (PDO). (A) El Niño events of 1957–1958, 1965–1966, 1968–1969, and 1972–1973.

for an annual average SST distribution from May of one year to April of the next, the typical period during which El Niño runs its course. For ordinary El Niño events, the maximum SST anomaly is near the dateline, but for largest El Niño events (1972–1973, 1982–1983, and 1997–1998), the maximum lies eastward toward the coast of South America. The typical SST distribution for Pacific Decadal Oscillation shares warmth in the eastern Pacific, but anomalously high SSTs extend farther from the equator than they do during El Niño events (Fig. 1C). Virtually all of the evidence showing that the equatorial Pacific was warmer at ca. 3–4 Ma than today, however, comes from analyses of cores from the Ocean Drilling Project taken within 1–2° of the equator and at restricted longitudes. Thus, although these paleoceanographic data provide a bulwark in the argument for a permanent El Niño climate in pre–Ice Age time, this two-point difference between eastern and western Pacific equatorial SSTs allows a range of possible SST distributions in the central equatorial Pacific and places no constraint on temperatures off the equator.

Differences among El Niño teleconnections can also be used to address the sea-surface temperature distribution in late Miocene-early Pliocene time. Toward that end, we present a synthesis of differences between paleo- and present-day climates, and we compare them with the teleconnections associated with different El Niño events and with those associated with the Pacific Decadal Oscillation. As will be clear later in this paper, for many regions of the world, teleconnections associated with warm sea-surface temperatures in the eastern equatorial Pacific have not been recognized, and presumably if they exist, they are too small or inconsistent to be detected. Moreover, late Miocene-early Pliocene climate differed from present-day climate in ways not associated with El Niño–like patterns. For instance, the northern latitudes were largely ice-free, and an ice-free Arctic surely affected climates on neighboring high-latitude land. Moreover, with a warm Arctic, one would expect the atmospheric circulation to differ sufficiently to alter El Niño teleconnection patterns. It follows that differences between paleo- and modern climates cannot be expected to match, even qualitatively, El Niño teleconnections patterns everywhere. We approach this not with the conviction that El Niño and its teleconnections should match differences between paleo- and modern climates everywhere, but with surprise that such patterns can be mimicked in as many regions as they are.

In this paper, we summarize briefly, if nevertheless with more detail than most readers will choose to read carefully, both typical El Niño

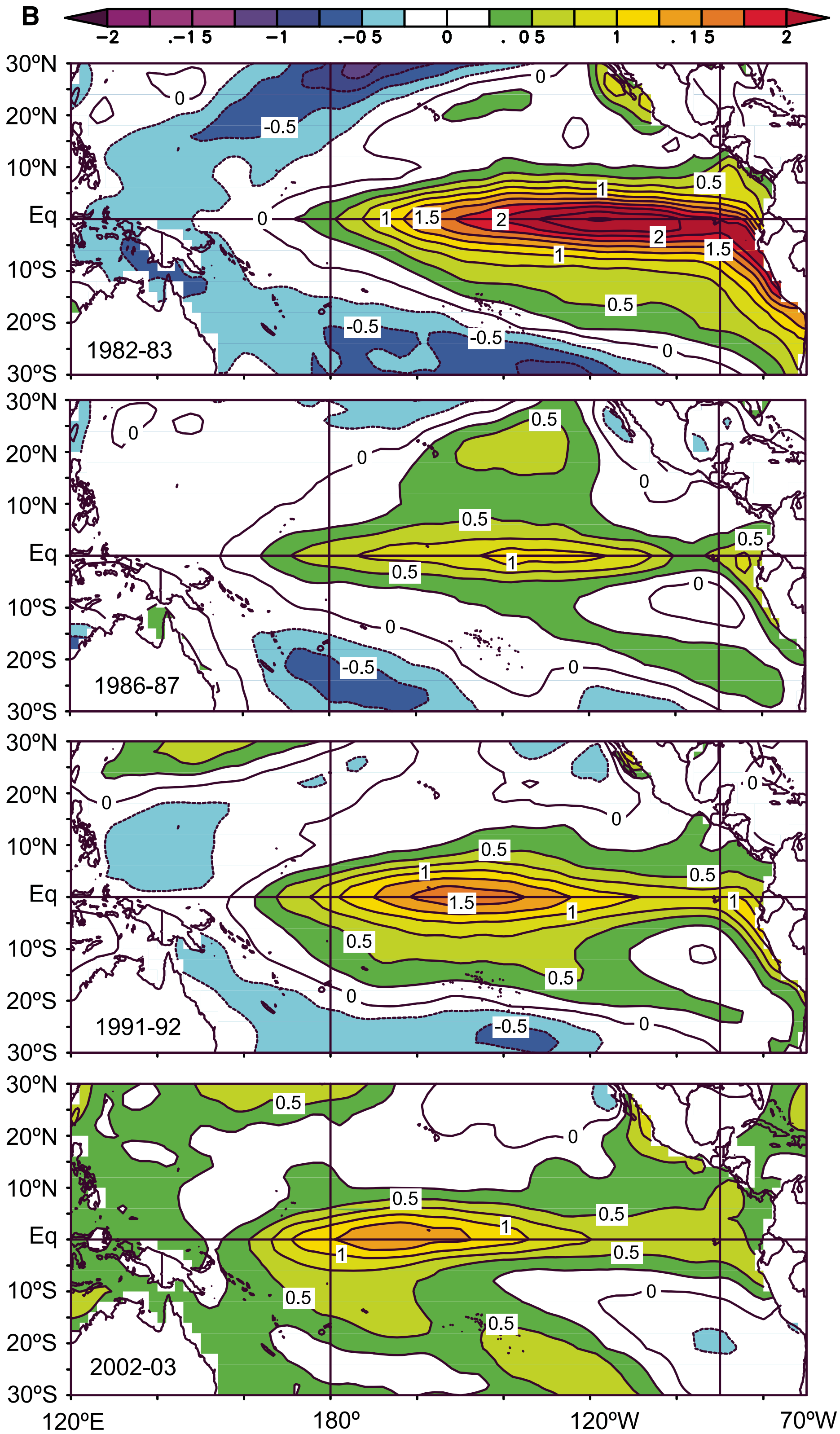


Figure 1 (*continued*). (B) El Niño events of 1982–1983, 1986–1987, 1991–1992, and 2002–2003.

teleconnections and paleoclimates for individual regions. For each region, we present analyses of the differences among such data to evaluate the extent to which some El Niño events (or the Pacific Decadal Oscillation) produce teleconnections that match differences between pre–Ice Age and modern climates better than others.

To illustrate modern climate teleconnections, we rely on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996), which is updated and available from http://www.cdc.noaa.gov, the Web site of the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) Climate Diagnostics Center, Boulder, Colorado. Rather than present maps for each region showing anomalies associated with each El Niño event, however, for most regions we show maps of teleconnections associated with one El Niño event, that of 1997–1998, the largest since 1900, in part because its teleconnections seem to match best late Miocene-early Pliocene regional climates. For some regions, we present maps of anomalies for other El Niño events and for the Pacific Decadal Oscillation. Although teleconnections tend to be strongest in shorter intervals than a year, and specifically in winter at many sites in the Northern Hemisphere, most geologic methods for inferring paleoclimate cannot differentiate signals that apply to specific seasons. Therefore, for nearly all cases, we show anomalies in temperature or precipitation for the period from May to April of an El Niño year, so as to capture all of the main phase.

For most regions, we also attempt to carry out an objective assessment of which El Niño event, or the PDO, best replicated the observed paleoclimate observations. For many reasons, making an objective comparison is difficult. As is known well, no two El Niño events are alike, and even if the Pacific SST distributions were the same, other sources of climatic variability would prevent climates in specific regions from being identical. Thus, even if paleoclimatic data and modern climate measurements were perfect, some disagreement would be inevitable. For some areas (e.g., Arctic), modern data are hardly devoid of error. Moreover, the marked warming there over the past decades obviously improves correlations of pre–Ice Age warmth with teleconnections associated with recent El Niño events. Quantitatively, many differences between paleo- and present climates differ by much larger amounts than anomalies associated with modern teleconnections, so that scaling differences among them is risky. At the opposite extreme, much of the paleoclimate data are qualitative—“wetter” or “drier” by

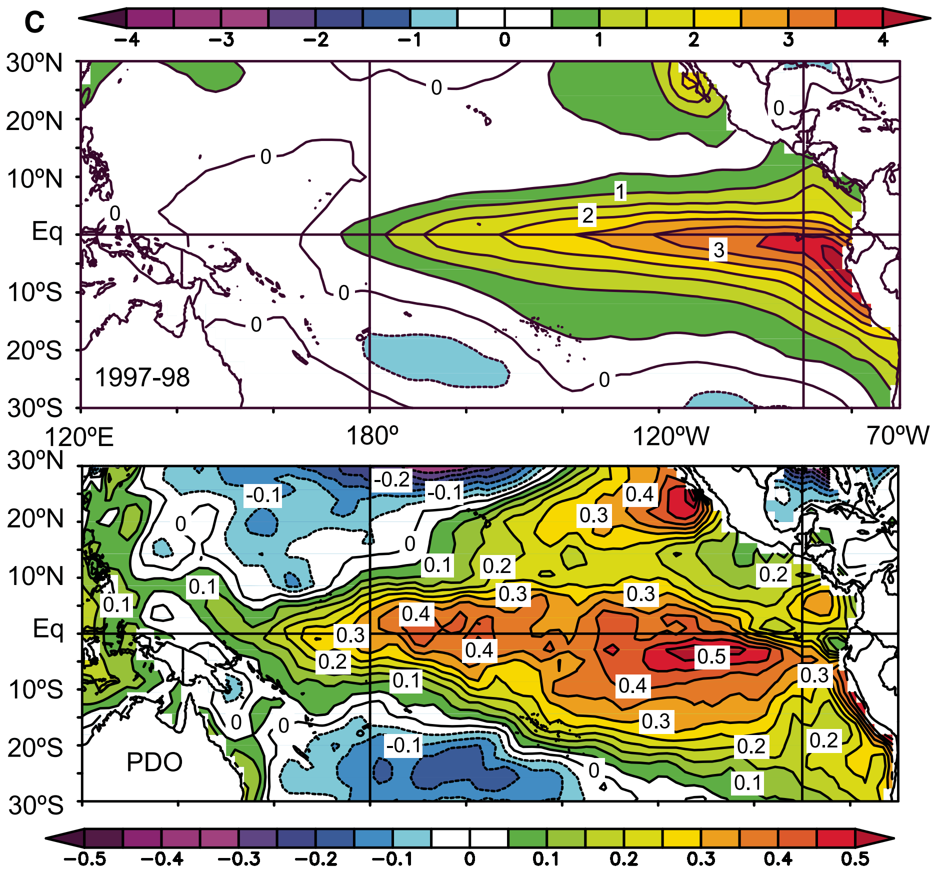


Figure 1 (*continued*). (C) El Niño event of 1997–1998 and PDO, with different SST scales for each, which are different also from those in (A) and (B). For the El Niño events, we used the extended reconstructed sea-surface temperatures of Smith and Reynolds (2003, 2004) and updated, for which anomalies were calculated relative to the average in the period 1971–2000. For the PDO, we used a compilation of sea-surface temperatures from the NCEP/NCAR Reanalysis project (Kalnay et al., 1996). Maps were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

some unspecified amount. For many regions, the paleoclimate data come not from the heart of major recurring teleconnections, but from the fringes. Anomalies correlated with the PDO are smaller than those associated with El Niño events, which seems obvious because of the smaller SST anomalies that correlate with the PDO than with El Niño events, but this difference makes scaling of modern anomalies to paleoclimate anomalies problematic. With these limitations in mind, we pursued the following approaches for temperature and precipitation.

For temperatures, we simply calculated the correlation of pre–Ice Age differences from the present with El Niño teleconnections for the different El Niño events. For each region and for El Niño event j, with n locations i with the estimated paleo- minus modern temperature anomaly, p_i, and modern teleconnections, $m_{i,j}$, we calculated:

$$C_j = \frac{\sum_{i=1}^{n} p_i m_{i,j}}{\sqrt{\sum_{i=1}^{n} p_i^2}\sqrt{\sum_{i=1}^{n} m_{i,j}^2}} \qquad (1)$$

Thus, for each region, we compared correlations for the different El Niño events j. For the PDO, we regressed temperatures against the PDO index of Mantua et al. (1997), and so for values of $m_{i,PDO}$, we used those temperatures to estimate C_{PDO}.

Where we had only qualitative inferences of wetter or drier climates, we computed binary statistics. We used the same mathematics as in (1), but for (nearly) all entries, p_i and $m_{i,j}$ equal either +1 or −1. (For a few, one of them equals zero.) For the PDO, we computed correlations of precipitation anomalies with the PDO index and took $m_{i,PDO}$ to be +1 or −1, according to the sign of the correlation. As a measure of significance, we calculated the probability that a given number (or more) of the sites in a region would agree with a random pattern of +1s and −1s drawn from a binomial distribution with probability 0.5 at each site. This measure undoubtedly overestimates significance of El Niño correlations, because individual sites are not all independent.

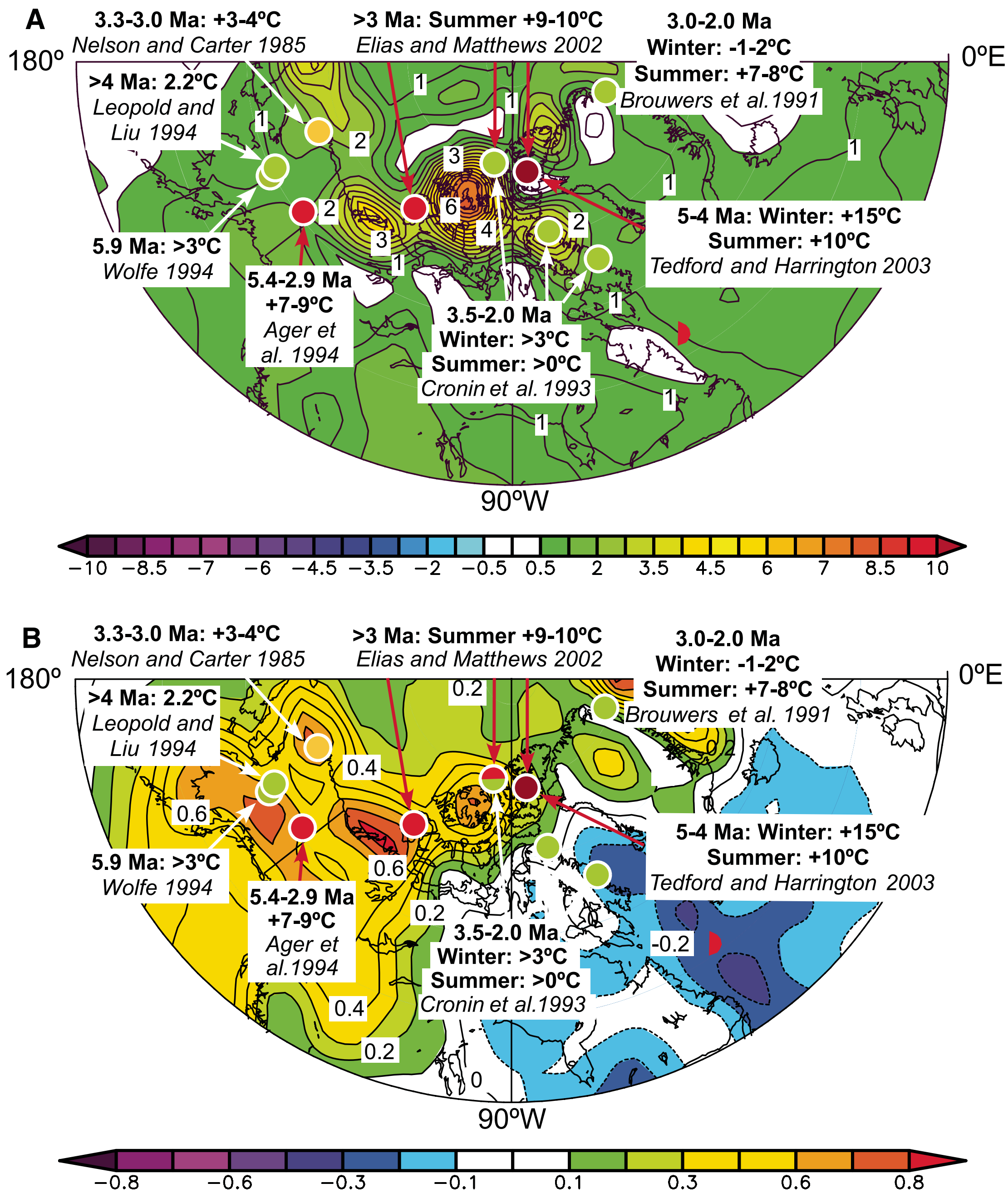
REGIONAL DISCUSSION

We discuss temperature or precipitation data from twelve regions, beginning in the Western Hemisphere with Alaska and the Arctic, and moving southward, then with Europe and Africa, and finally Asia and Australia.

Canada, Alaska, and the Arctic

Warm winters characterize Canada, particularly western and southern Canada, and Alaska during El Niño events (Halpert and Ropelewski, 1992; Horel and Wallace, 1981; Kiladis and Diaz, 1989; Rasmusson and Wallace, 1983; Ropelewski and Halpert, 1986; Trenberth et al., 2002). Kiladis and Diaz (1986) also noted that southern Canada and the northern United States were especially warm during the large 1877–1878 El Niño. Ice on the Great Lakes was thin during the 1997–1998 winter (Assel, 1998), and most of Canada was warmer than normal (Fig. 2A), as is the case during positive phases of the Pacific Decadal Oscillation (Fig. 2B). Moreover, westernmost Canada (Mason and Goddard, 2001), southern Canada (Shabbar et al., 1997), and the Great Plains of the middle of the continent (Diaz et al., 2001) receive less precipitation during El Niño winters than normal. Data from the Arctic are less clear, and arguments for an effect of El Niño rely more on spectral analyses showing power in the ENSO band (~2–7 yr) than direct correlations of time series (e.g., Gloersen, 1995; Jevrejeva et al., 2003, 2004).

Several studies of pollen (Ager, 1994; Ager et al., 1994; Leopold and Liu, 1994; Nelson and Carter, 1985) and of plant macrofossils (Wolfe, 1994) suggest that Alaska and Canada were warmer in late Miocene and early Pliocene time than today (Fig. 2 and Table 1). From fossil pollen found in different parts of Alaska, Ager et al. (1994) suggested that between 5.4 and 2.9 Ma the mean annual temperature was 7–9 °C warmer than today, and Leopold and Liu (1994) inferred that southern Alaska near Anchorage was 2.2 °C warmer in late Miocene and Pliocene time than today. From an analysis of fossil leaf margins,



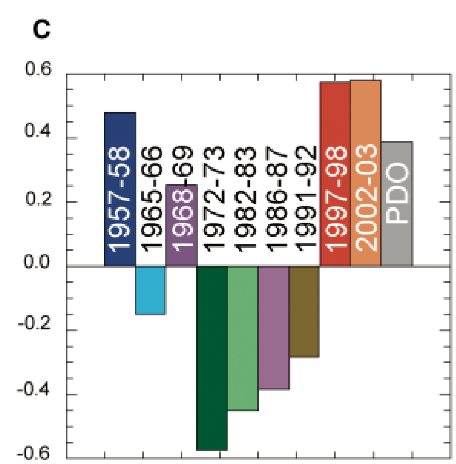


Figure 2. Comparisons of inferred differences between late Miocene-early Pliocene and present-day temperatures from Alaska, Canada, and northern Greenland with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B) such differences are superimposed on maps (A) of temperature anomalies in °C for the period May 1997 to April 1998, compared with the average for the period 1968–1998 and (B) of temperatures between 1949 and 2003 regressed on the Pacific Decadal Oscillation Index. In (C) correlations of paleotemperature anomalies with El Niño teleconnections are shown for each event.

Wolfe (1994) deduced that at 5.9 Ma temperatures in the Alaska Range were >3 °C higher than today.

Similarly, both the Canadian Arctic and Northern Greenland seem to have been warmer in late Miocene and Pliocene time, in some cases by several degrees Celsius, than today. Again, inferences are derived from pollen (e.g., Brigham-Grette and Carter, 1992; Willard, 1996) and plant microfossils (Funder et al., 1985), plus marine organisms such as ostracodes (Brouwers, 1994; Brouwers et al., 1991; Cronin et al., 1993), fossil beetles (Elias and Matthews, 2002), and fossil mammals (Tedford and Harington, 2003). Although dating is imprecise for many of these inferences and others appear to reflect conditions near the onset of Northern Hemisphere Glaciation, some do indicate large temperature differences before ice sheets began to form. For example, Tedford and Harington (2003) inferred that at 4 to 5 Ma winter temperatures on Ellesmere Island must have been 15 ºC warmer than at present, and summer temperatures 10 ºC warmer, so that the climate resembled that presently in Labrador 20° to the south.

We have not found paleoclimatic inferences from southern Canada that can be compared with modern El Niño teleconnections or anomalies associated with the Pacific Decadal Oscillation, except the obvious fact that during much of the past 2.7 Myr, ice sheets have covered this region, but before that time, they seem to have been absent. This is consistent with permanent El Niño conditions, which would increase summertime ablation (e.g., Huybers and Molnar, 2007).

Much of this region warms during most, but not all, El Niño events and during the positive phase of the PDO (Fig. 2). Superimposed on El Niño correlations, however, is background warming, which has been particularly strong over the past 20 yr. The highest correlation of El Niño teleconnections to paleoclimate anomalies is for 2002–2003 (Fig. 2C), surely a result of global warming, and the general increase in high-latitude temperatures over the past 15 yr may not allow reliable inferences of El Niño's role. The safe conclusion is that paleoclimate data from Canada do not do a very good job of distinguishing which El Niño or the PDO offers the best prototype for pre–Ice Age tropical conditions.

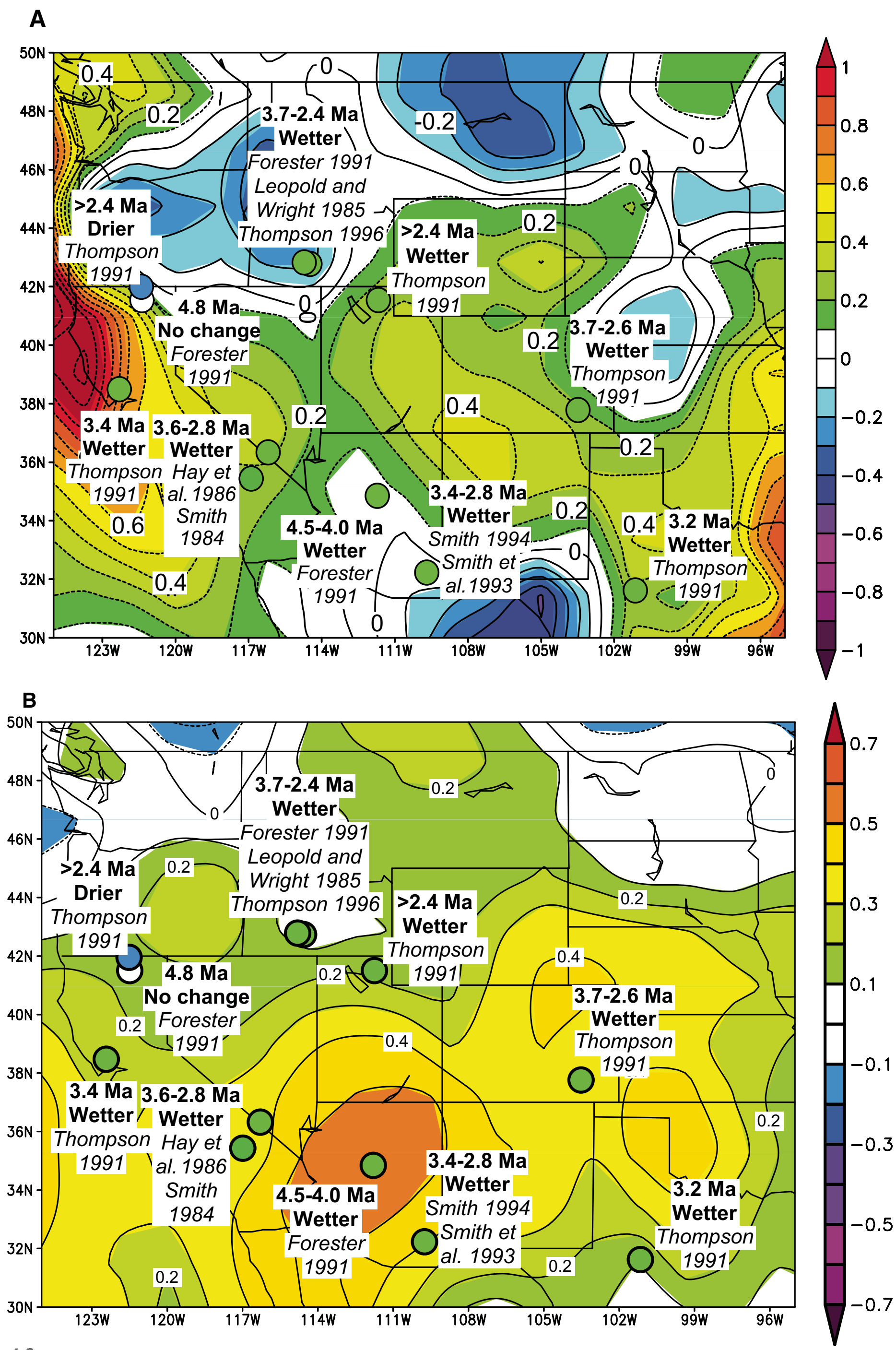
Midwestern and Western United States

During El Niño years (Fig. 3A) and during positive phases of the Pacific Decadal Oscillation (Fig. 3B), the typically arid southwestern United States receives more rainfall than

TABLE 1. SUMMARY OF DIFFERENCES BETWEEN PRE–ICE AGE AND PRESENT-DAY TEMPERATURES

Latitude (°N)	Longitude (°E)	Age (Ma)	Δ Temp (°C)*	Reference
Alaska, Canadian Arctic, and Greenland				
70	–150	3.3–3.0	+3–4	Nelson and Carter (1985)
63.8	–149.0	5.9	>3	Wolfe (1994)
63.9	–148.9	6–4	+3.2	Leopold and Liu (1994)
65.8	–145.2	5.4–2.9	+7–9	Ager et al. (1994)
74	–124	5–3	+11.1 S	Elias and Matthews (2002)
74	–124	5–3	+20.4 W	Elias and Matthews (2002)
79.9	–99.5	3.5–2.0	>0 S	Cronin et al. (1993)
79.9	–99.5	3.5–2.0	>3 W	Cronin et al. (1993)
79.9	–99.5	3	+10 S	Elias and Matthews (2002)
79.9	–99.5	3	+14–20 W	Elias and Matthews (2002)
79	–82	>3.3	+10 S	Elias and Matthews (2002)
79	–82	>3.3	+14.8 W	Elias and Matthews (2002)
78.55	–82.37	5–4	>10 S	Tedford and Harington (2003)
78.55	–82.37	5–4	>15 W	Tedford and Harington (2003)
70	–71	3.5–2.0	>0 S	Cronin et al. (1993)
70	–71	3.5–2.0	>3 W	Cronin et al. (1993)
65	–65	3.5–2.0	>0 S	Cronin et al. (1993)
65	–65	3.5–2.0	>3 W	Cronin et al. (1993)
80	–25	3.0–2.0	>7–8 S	Brouwers et al. (1991)
80	–25	3.0–2.0	<1–2 W	Brouwers et al. (1991)
Southeastern United States and the margin of the Gulf of Mexico				
18.7	–97	~5–2	cooler	Machain-Castillo (1986)
18.5	–96	~3	cooler	Graham (1989a, 1989b)
27.25	–82.66	3.5–3.0	–2.4 S	Cronin (1991)
27.25	–82.66	3.5–3.0	–0.6 W	Cronin (1991)
27.35	–82.43	3.6–2.6	no change	Willard (1994)
25.78	–80.28	3.5–3.0	+2.2 S	Cronin (1991)
25.78	–80.28	3.5–3.0	–2.1 W	Cronin (1991)
34.	–79.	3.5–3.0	–0.4 S	Cronin (1991)
34.	–79.	3.5–3.0	–1.0 W	Cronin (1991)
35.4	–76.8	3.5–3.0	+3.1 S	Cronin (1991)
35.4	–76.8	3.5–3.0	+2.3W	Cronin (1991)
36.	–76.5	4.0–2.9	+3–5 W	Willard (1994)
36.	–76.5	4.0–2.9	+2–2.5	Willard (1994)
37.0	–76.5	3.5–3.0	+8.1 S	Cronin (1991)
37.0	–76.5	3.5–3.0	+5.7 W	Cronin (1991)
41.	–71.	3.5–3.0	+8.0 S	Cronin (1991)
37.0	–76.5	3.5–3.0	+2.8 W	Cronin (1991)
Western Europe and North Africa				
39.3	–8.9	5.3–3.8	+~4	Fauquette et al. (1999)
36.5	–5	5.3–2.4	+~6	Fauquette et al. (1999)
35.2	–3.0	5.3–2.2	+6	Fauquette et al. (1999)
35.7	–1.1	5.3–3.2	+~6	Fauquette et al. (1999)
41.1	1.3	5.3–3	+1–10	Fauquette et al. (1999)
42.7	2.9	5.3–4.4	+~6	Fauquette et al. (1999)
43.3	3.5	5.3–4.3	+1–6	Fauquette et al. (1999)
43.5	4.5	4.3–4	+1.6–4.2	Fauquette et al. (1999)
43.7	6.3	5–3.4	+1–5	Fauquette et al. (1999)
36.5	10.5	5.3–5	+~6	Fauquette et al. (1999)
37.3	13.5	5.3–4.5	0	Fauquette et al. (1999)
West Africa				
23.0	–20.0	6.5–4.4	+3.5	Herbert and Schuffert (1998)
20.75	–18.6	3.7–2.6	warmer	Leroy and Dupont (1994, 1997)
Southwest Africa				
–25.5	13.0	4.5–3.2	+10	Marlow et al. (2000)
–19.7	10.5	~3.2	warmer	Dowsett (1989), Dowsett and Willard (1996)
India				
34	75	3.15–2.7	warmer	Agrawal (1988)
32	76	3.15–2.7	warmer	Sanyal et al. (2004)
31	77	>2.7	warmer	Gaur and Chopra (1984)
30.5	77.2	3.15–2.7	warmer	Sanyal et al. (2004)
27.5	85.3	>3	warmer	Igarashi et al. (1988)
China				
35.0	107.5	>3.5–3	warmer S	Ding et al. (1999)
35.1	107.65	>3.6	warmer S	Sun et al. (1998)
38.25	110.1	>3.5–3.1	warmer S	Sun et al. (1998)

*In general, differences refer to annual averages, but where shown, S is summer and W is winter.



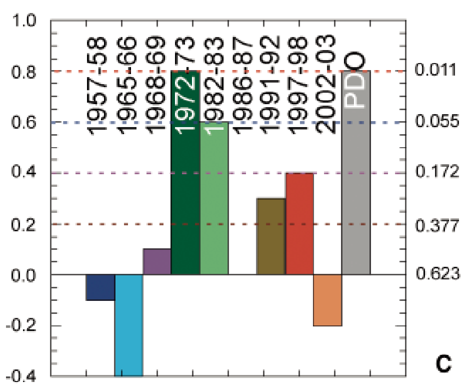


Figure 3. Comparisons of inferred differences between late Miocene-early Pliocene and present-day precipitation from the western United States with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B) such differences are superimposed on maps (A) of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996 and (B) of correlations of precipitation anomalies between 1949 and 2003 with the Pacific Decadal Oscillation Index. In (C) binary correlations of paleo-precipitation anomalies with El Niño teleconnections are shown for each event. On the right, numbers show probabilities of the fraction of the locations with positive correlations equaling or exceeding the value shown on the left, assuming that the probability obeys a binomial law with probability of agreement or disagreement equaling 0.5.

normal, particularly in summer (from April to November, according to Ropelewski and Halpert (1986)), and the north central and northwestern states receive less precipitation than normal (e.g., Cayan and Webb, 1992; Cook et al., 2000; Dettinger et al., 2000; Diaz et al., 2001; Lall and Mann, 1995; Mason and Goddard, 2001; Rasmusson and Wallace, 1983; Ropelewski and Halpert, 1986; Trenberth et al., 1998). Such a pattern is clear for 1997–1998 (Fig. 3). The 1877–1878 El Niño also was no exception; Kiladis and Diaz (1986) noted that the northern states were very warm, and, in San Francisco, rainfall during November to March 1878 was unusually high. Correspondingly, the opposite patterns occur during strong La Niña events (Cayan and Webb, 1992; Dettinger et al., 2000; Ropelewski and Halpert, 1989).

Numerous studies of late Miocene to early Pliocene climate of the western United States show moister climates at that time than today (Table 2) (e.g., Thompson, 1991; Thompson and Fleming, 1996; Webb et al., 1995). Forester (1991) and Thompson (1991) reported evidence of numerous lakes from southern Idaho southward to Arizona and southeastward to Texas in early Pliocene time (Fig. 3). In many areas where arid climates today leave saline deposits in internally drained basins, lakes seemed to have overflowed in late Pliocene time, for saline deposits are sparse (e.g., Hay et al., 1986; G.A. Smith, 1994; G.A. Smith et al., 1993; G.I. Smith, 1984). In some areas, fossil vertebrates, including fish (G.R. Smith and Patterson, 1994), reptiles, and mammals (Thompson, 1991; Thompson and Fleming, 1996), suggest lacustrine environments. Pollen assemblages from sites in the Snake River plain and southwest Idaho also imply cooler and wetter environments in late Miocene (Leopold and Wright, 1985) and in Pliocene time (Thompson, 1996). For California, Axelrod (1973, 1986) described a gradual shift from summer rain in Miocene time to winter rain with dry summers by middle Pliocene time, although imprecise dating

TABLE 2. SUMMARY OF DIFFERENCES BETWEEN PRE–ICE AGE AND PRESENT–DAY PRECIPITATION

Latitude (°N)	Longitude (°E)	Age (Ma)	Δ Precipitation (mm/yr)*	Reference
Western United States				
38.2	–122.7	3.4	Wetter S	Thompson (1991)
42.0	–121.5	>2.4	Drier	Thompson (1991)
41.5	–121.5	4.8	No difference	Forester (1991)
35.7	–117.4	3.2–2.6	Wetter	G.I. Smith (1984)
36.5	–116.2	3.2–2.4	Wetter	Hay et al. (1986)
42.9	–115.8	3.5–2.5	Wetter	Thompson (1996)
42.8	–115.3	3.7–3.3	Wetter	Forester (1991)
42.7	–114.9	3.5–3	Wetter	Leopold and Wright (1985)
42.7	–114.9	3.7–3.3	Wetter	Forester (1991)
35	–112	4.5–4.0	Wetter	Forester (1991)
41.5	–111.5	>2.4	+60	Thompson (1991)
31.8	–110.3	3.4–2.8	Wetter	G.A. Smith (1994)
31.8	–110.3	3.4–2.8	Wetter	G.A. Smith et al. (1993)
37.5	–103.5	3.7–2.6	Wetter	Thompson (1991)
32.0	–101.5	3.2	Wetter	Thompson (1991)
South America				
0 to –10	–70 to –45	>4	Drier	Hovan (1995)
–19 to –21.6	–70	3.49	Wetter	Allmendinger et al. (2005)
–19.75 to –23	–70	6–3.3	Wetter	Hartley and Chong (2002)
–38	–59	5–2	Wetter	Zarate and Fasana (1989)
Western Europe and North Africa				
39.3	–8.9	5.3–3.8	+400	Fauquette et al. (1999)
36.5	–5	5.3–2.4	+100–300	Fauquette et al. (1999)
35.2	–3.0	5.3–2.2	+350	Fauquette et al. (1999)
35.7	–1.1	5.3–3.2	+350	Fauquette et al. (1999)
41.1	1.3	5.3–3	+600	Fauquette et al. (1999)
42.7	2.9	5.3–4.4	+360–600	Fauquette et al. (1999)
43.3	3.5	5.3–4.3	+350–800	Fauquette et al. (1999)
43.5	4.5	4.3–4	+500–900	Fauquette et al. (1999)
43.7	6.3	5–3.4	+500–900	Fauquette et al. (1999)
36.5	10.5	5.3–5	+150–350	Fauquette et al. (1999)
37.3	13.5	5.3–4.5	Drier	Fauquette et al. (1999)
Chad and Central Africa				
16.25	17.5	7.4–5.2	Wetter	Louchart et al. (2004), Vignaud et al. (2002)
16.0	18.9	3.5–3.0	Wetter	Brunet et al. (1995)
Southwest Africa				
–25 to –28	15 to 16.5	~3.5	Wetter	Segalen et al. (2002)
–29	17	~10–5	Wetter	Scott (1995)
East Africa				
12.6	37.1	~8	Wetter	Yemane et al. (1985)
11.1	40.6	3.5–3.2	+400	Bonnefille (1984), Bonnefille et al. (1987)
10.5	40.4	5.8–4.4	Wetter	Boisserie (2004), WoldeGabriel et al. (1994, 2001)
7	39	2.5–2.35	Drier	Bonnefille (1983, 1984, 1995)
5	36	4.1–2.95	Wetter	Bonnefille (1995), Wesselman (1995), Williamson (1985)
~4	36	≥3.9	Wetter	Leakey et al. (1995, 1996)
2.3	36.1	4.2–3.9	Wetter	Leakey et al. (1996)
0.75 to 1.5	35.8 to 36	12.6–6.5	Wetter	Hill (1995)
0.75 to 1.5	35.8 to 36	6.3–4.5	Wetter	Pickford and Senut (2001), Pickford et al. (2004)
–3.2	35.2	3.7	No difference	Bonnefille (1984)
India				
34	75	3.15–2.7	“Subtropical”	Agrawal (1988)
32	76	3.15–2.7	Wetter	Sanyal et al. (2004)
31	77	>2.7	Wetter	Gaur and Chopra (1984)
30.5	77.2	3.15–2.7	Wetter	Sanyal et al. (2004)
27.5	85.3	>3	Wetter?	Igarashi et al. (1988)
China				
35.0	107.5	>3.5–3	Drier S	Ding et al. (1999)
35.1	107.65	>3.6	Drier S	Sun et al. (1998)
38.25	110.1	>3.5–3.1	Drier S	Sun et al. (1998)
Australia				
–33	121	>3	Wetter	Bint (1981)
–17	123	>3	Wetter	Kershaw et al. (1994)
–23	134	8–5	Wetter	Archer et al. (1995)
–27.2 to –28.6	136	4–2	Wetter	Fujioka et al. (2005)
–30	140	>3	Wetter	Kershaw et al. (1994)
–38	142	4.35	Wetter	Bowler (1976)
–19	145	3.4	Wetter	Archer et al. (1995)
–36	145	4.5	Wetter	Archer et al. (1995)
–21	148	>3	Wetter	Kershaw et al. (1994)
–31	148	~4	+700–1000	Martin (1994)
–32	148	~4	Wetter	Archer et al. (1995)
–30	153	>5	Wetter	Kershaw et al. (1994)

*In general, differences refer to annual averages, but where shown, S is summer, W is winter.

denies his observations as much support for El Niño–like conditions as those mentioned earlier in this paper.

Although the paleoclimate data replicate approximately the canonical El Niño teleconnection pattern of increased precipitation across the southern part of the region and reduced amounts across the northern part, the east-west-trending boundary between them seems to shift from one event to the next (e.g., Fig. 3A). The PDO shows a similar pattern (Fig. 3B), but with the boundary shifted far enough north that most of the western United States receives more precipitation during positive PDO indices than negative ones. Thus, the paleoclimate data are consistent with teleconnections associated with most El Niño events and with the PDO. In general, the PDO and the largest El Niño events (1972–1973, 1982–1983, and 1997–1998) correlate best with the pre–Ice Age differences (Fig. 3C).

Southeastern United States, Gulf of Mexico, and Mexico

Although most of the world warms during El Niño events, the region surrounding the Gulf of Mexico and extending both northeastward up the coast of the United States and westward into Mexico both cools (Fig. 4) and receives more precipitation than normal, particularly in winter (October–March) (e.g., Cayan and Webb, 1992; Cook et al., 2000; Curtis and Adler, 2003; Curtis et al., 2001; Dettinger et al., 2000; Diaz et al., 2001; Enfield and Mestas-Nuñez, 2000; Kiladis and Diaz, 1989; Mason and Goddard, 2001; Ropelewski and Halpert, 1986; Zorn and Waylen, 1997). Again, large El Niño events have a marked effect on this region (e.g., Kiladis and Diaz, 1986). In fact, relatively low temperatures and higher than normal precipitation in the southeastern United States persisted into the spring of 1998. Moreover, La Niña winters tend to be drier than normal (Cayan and Webb, 1992; Dettinger et al., 2000; Ropelewski and Halpert, 1989).

This pattern of cold, wet winters can be understood as the result of a deflection of the subtropical jet due to a stronger Hadley Circulation over the eastern Pacific or in terms of Rossby waves emanating from the equatorial Pacific (e.g., Barsugli and Sardeshmukh, 2002; Branstator, 1983, 1985; Hoskins and Ambrizzi, 1993; Hoskins and Karoly, 1981; Sardeshmukh and Hoskins, 1988; Trenberth et al., 1998; Webster, 1981).

Although most of the world was warmer in early Pliocene time (ca. 5–3 Ma) than today, numerous studies show that the region surrounding the Gulf of Mexico and the southeastern seaboard of the USA was cooler (and wetter) (Figs. 4 and 5; Table 1). Assemblages of marine ostracodes allow quantitative estimates of differences in temperatures for both winter and summer seasons (e.g., Dowsett and Poore, 1990), and they show that the shallow water around Florida and the southeastern states was cooler by 1–2.5 °C than today in both winter and summer (Fig. 5) (e.g., Cronin, 1991; Cronin and Dowsett, 1990, 1996). The boundary separating areas that were cooler or warmer from those today lies in Virginia (Figs. 4 and 5) (Cronin, 1991; Cronin and Dowsett, 1990, 1996; Dowsett and Poore, 1991; Dowsett and Wiggs, 1992; Groot, 1991; Willard, 1994). In addition, Willard (1994; Willard et al., 1993) interpreted early Pliocene pollen deposited in Florida as suggesting more temperate climates than today. Evidence from the southwest corner of the Gulf of Mexico suggests that this region also was cooler in early Pliocene time than today. Machain-Castillo (1986) reported an assemblage of early Pliocene ostracodes from the southwestern Gulf of Mexico that T. Cronin (2001, personal commun.) associated with lower temperatures than today. Moreover, Graham (1989a, 1989b) inferred from an early Pliocene floristic assemblage in central Mexico near Veracruz (18.5°N, 96°W) that mean annual temperatures there were 2–3 °C cooler than today. Although the southwestern Gulf of Mexico did not cool as much in 1997–1998 (Figs. 4 and 5) as it has in some El Niño years, the lower temperatures inferred by Graham and Cronin are consistent with a similarity between El Niño teleconnections and paleoclimate anomalies.

In seeking correlations between early Pliocene differences from present-day climates with El Niño teleconnections, we considered

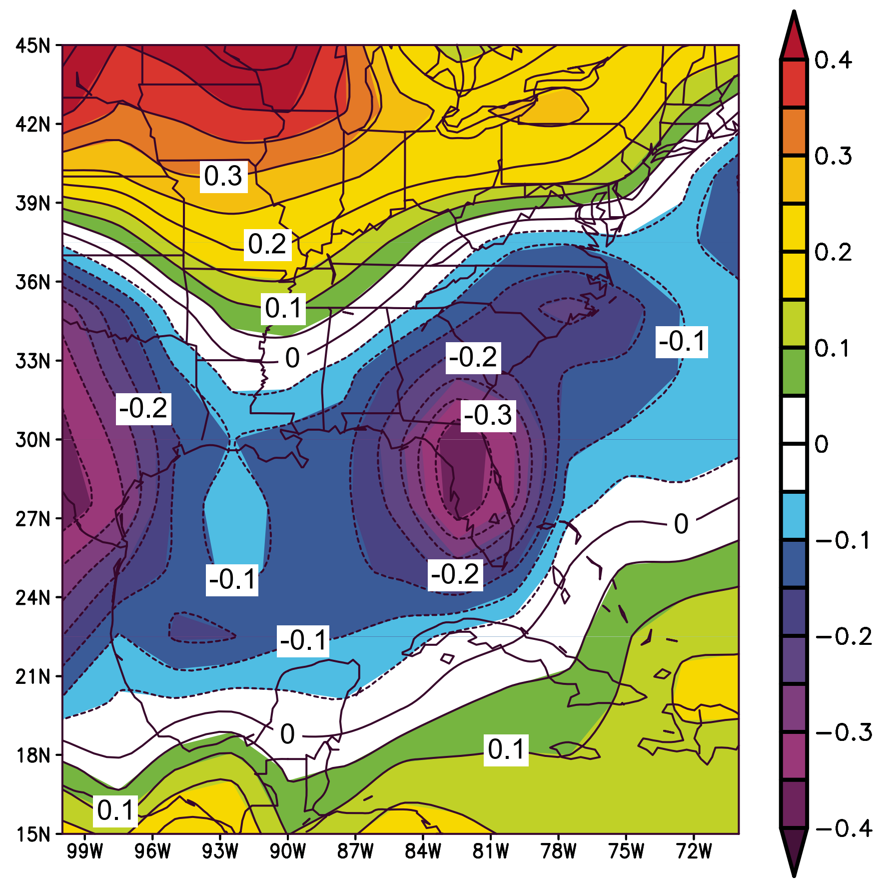


Figure 4. Map of composite annual temperature anomalies in °C from the southeastern United States and the region surrounding the Gulf of Mexico for the nine El Niño years, 1957–1958, 1965–1966, 1968–1969, 1972–1973, 1982–1983, 1986–1987, 1991–1992, 1997–1998, and 2002–2003, each covering the twelve months from May of the first year to April of the second, and referenced against the mean monthly anomalies between 1968 and 1996. Note the lowered temperatures in the area surrounding the Gulf of Mexico and the southeastern United States and the increased temperatures north of ~34°N, similar to that shown by paleo-temperature anomalies shown in Figure 5.

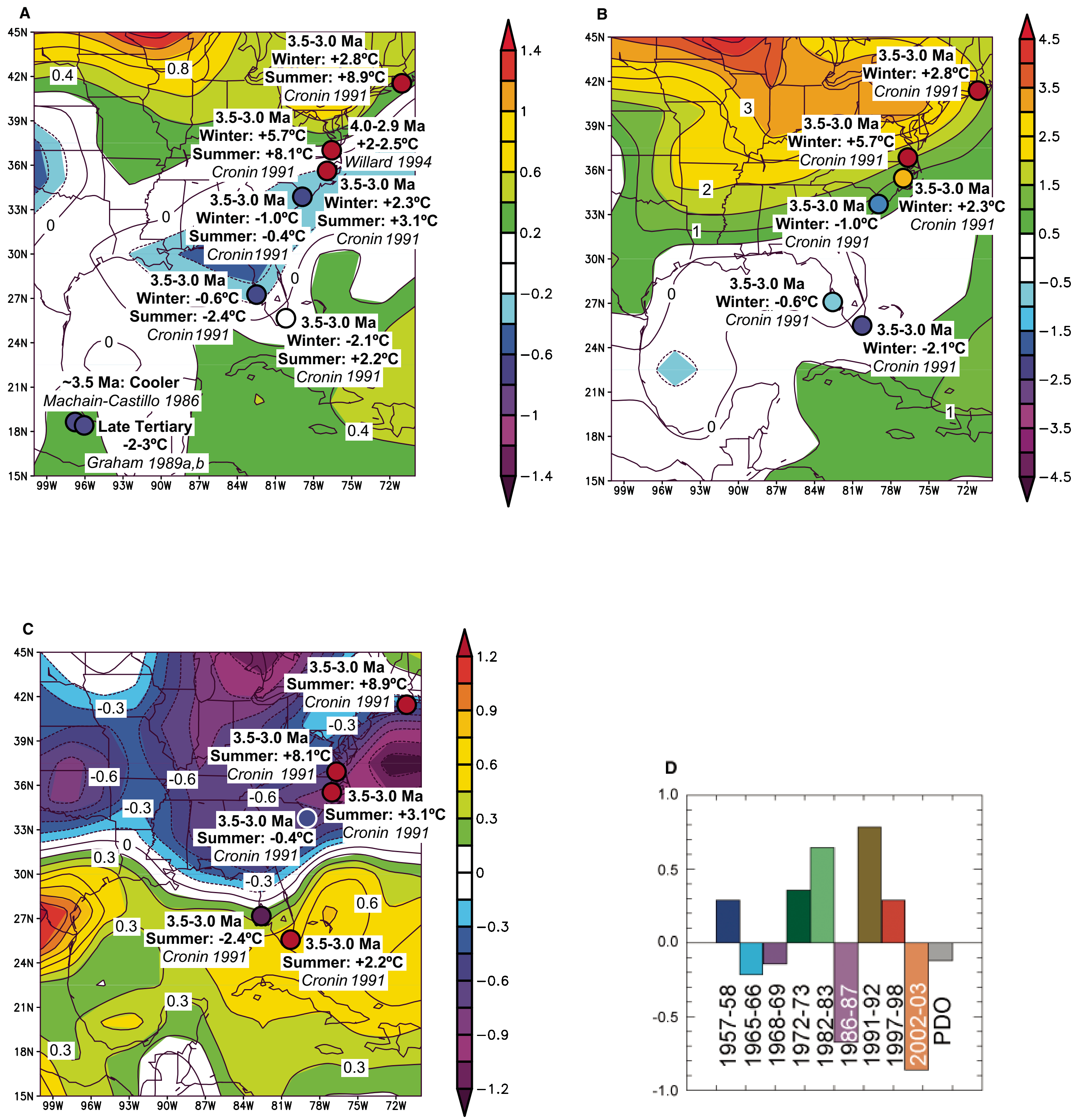


Figure 5. Comparisons of inferred differences between early Pliocene and present-day temperatures from the southeastern United States and the region surrounding the Gulf of Mexico. In (A), (B), and (C) such differences are superimposed on maps (A) of annual temperature anomalies in °C for the period May 1997 to April 1998, (B) of winter (December 1997 to February 1998) temperatures, and (C) summer (June to August 1997) temperatures, all compared with averages for the period 1968–1996. In (D) correlations of paleo-temperature anomalies with El Niño teleconnections are shown for each event.

both annual averages and seasonal differences separately. As seen in Figure 5C, anomalies associated with the 1997–1998 summer do not match well those of Cronin's (1991; Cronin and Dowsett, 1990, 1996) early Pliocene summer temperatures. Indeed, consideration of separate seasonal anomalies yields near-zero or negative correlations between pre–Ice Age and El Niño teleconnections except for the 1991–1992 El Niño. We assume that the poor correlations result at least in part to additional sources of Pliocene temperature anomalies that cannot be correlated with El Niño; for instance, the much warmer summers in the northeastern United States than present surely result in part from a warmer early Pliocene Arctic. When annual averages are considered, the 1991–1992 El Niño shows the highest correlation, and the others that correlate positively are the largest El Niño events (1957–1958, 1972–1973, 1982–1983, and 1997–1998). The large negative correlation for 2002–2003 may reflect the bias introduced by rapid global warming over the past decade.

We emphasize that the shift from cooler to warmer early Pliocene differences at approximately the same latitude as that observed for the average El Niño teleconnection strongly supports the inference of a pre–Ice Age El Niño state. The analysis in Figure 5D, however, is unsatisfying because a shift of a few degrees in the latitude of the boundary between positive and negative anomalies for paleo-data degrades the correlation without obscuring the basic pattern. Accordingly, the differences among the various El Niño events does not provide a strong argument for selecting one as most representative of pre–Ice Age time.

South America

One of the most robust teleconnections associated with El Niño is low rainfall over the Amazon Basin in northeastern Brazil, and commonly also in Venezuela and eastern Colombia, especially in boreal winter, but also in the preceding late summer and autumn (e.g., Aceituno, 1988; Barros et al., 2002; Coelho et al., 2002; Curtis et al., 2001; Dettinger et al., 2000; Enfield and Mestas-Nuñez, 2000; Kiladis and Diaz, 1986; Lau and Sheu, 1991; Lyon, 2004; Mason and Goddard, 2001; Nicholls, 1991; Ropelewski and Halpert, 1987, 1996). Correspondingly, strong La Niña events are associated with heavier than normal rainfall and lower temperatures (e.g., Aceituno, 1988; Barros et al., 2002; Coelho et al., 2002; Nicholls, 1991; Ropelewski and Halpert, 1989). Nicholls (1991), in particular, reported "upwards of 200,000 deaths" from a famine due to drought in northeastern Brazil in 1877–1878. Consistent with this pattern, low precipitation characterized the 1997–1998 El Niño (Fig. 6A), but by no means was this anomaly greatest among El Niño events; a strong El Niño does not necessarily correlate with a strong drought. In fact, the correlation of rainfall with the PDO index is positive: on decadal time scales, more rain falls in the Amazon Basin when the eastern Pacific is warm (Fig. 6B). We hesitate to draw firm conclusions because the time series is too short to separate the PDO effect from the influence of ENSO.

The paleoclimatic record for northeastern South America is sparse at best, but a couple of arguments do suggest a difference between early to late Pliocene time. First, Hovan (1995) showed that aeolian deposition in the eastern Pacific was lower in late Miocene and early Pliocene time than later. South America, to the east, offers the only plausible source of aeolian sediment. As deposition rates of aeolian sediment depend mostly on the aridity of the source region (e.g., Rea, 1994), Hovan (1995) interpreted his observations to suggest that northern South America, including the Amazon Basin, was more arid in late Miocene and early Pliocene time than later. He also reported that grain sizes were larger before 3–4 Ma, and because stronger winds are needed to carry larger grains (e.g., Rea, 1994), this result suggests that easterly winds were stronger in late Miocene and early Pliocene time than later. Note that although easterly winds over the central Pacific weaken during El Niño events, those over the easternmost Pacific strengthen at such times (Harrison and Larkin, 1998). Thus, both the decreased accumulation rates, which suggest a less arid source in northern South America than during late Miocene and early Pliocene time, and the decrease in grain sizes, which implies a decrease in easterly winds, are consistent with a change from an El Niño state to the present weak La Niña state.

Additional indirect evidence can be taken to suggest a more arid late Miocene and early Pliocene climate than today in Venezuela. Nesbitt and Young (1997) showed that pelagic sedimentation in the Venezuelan Basin increased dramatically at ca. 4 Ma, which they attributed to increased storm activity in the Atlantic and Caribbean. The change, however, might also be due to increased erosion and sediment transport rates by a wetter, more La Niña–like climate since ca. 4 Ma.

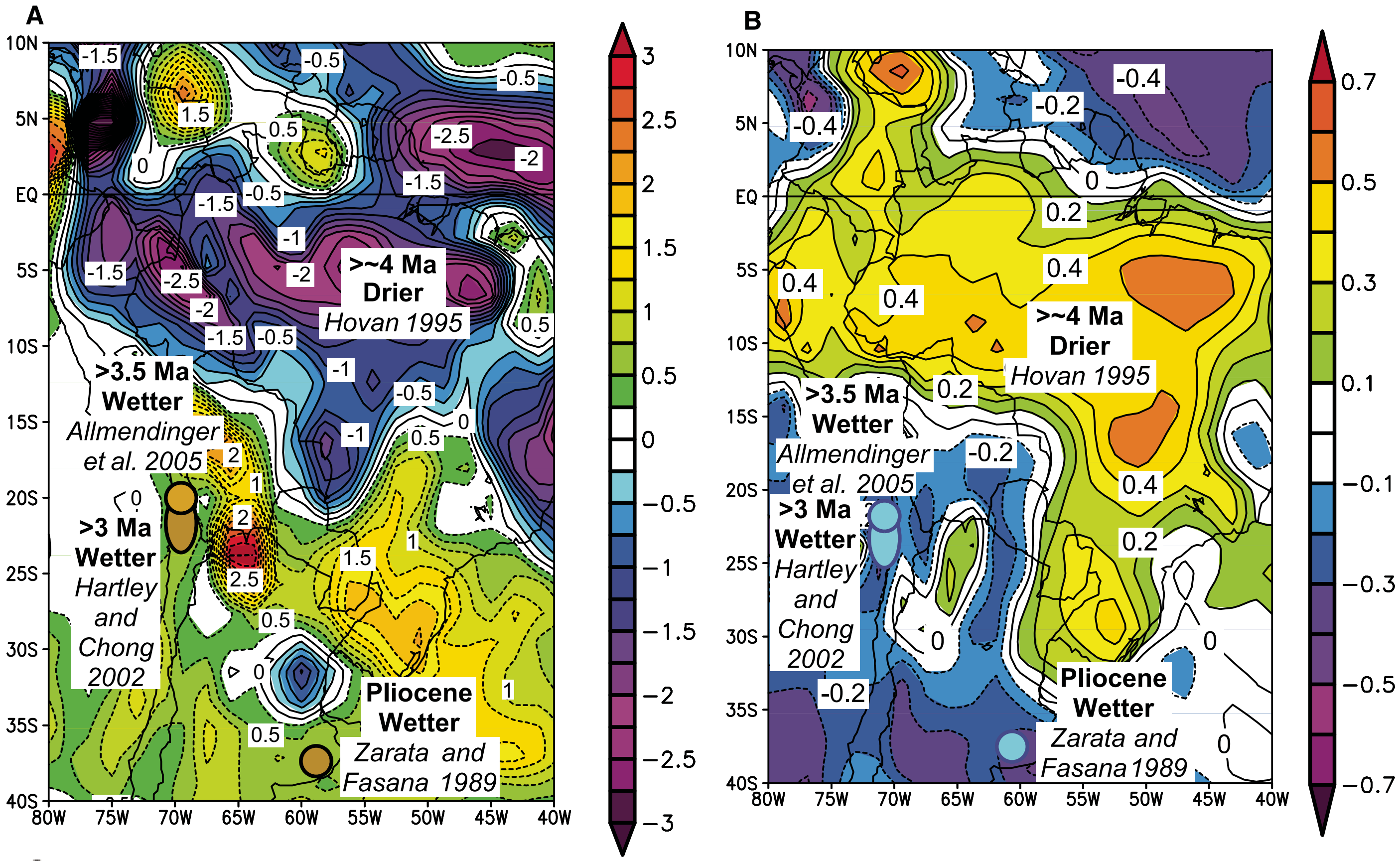
Obviously, the arguments given in this paper, from work of Hovan (1995) and Nesbitt and Young (1997), are indirect. Nevertheless, if neither requires a shift toward greater aridity in the Amazon Basin and northern South America at the time of the onset of Northern Hemisphere glaciation, both are consistent with such a change.

The sea-surface temperature of the equatorial Pacific off the west coast of South America famously warms during El Niño, and rain falls heavily inland of the warmer ocean. The warming and increased rainfall extend southward as far as central Chile. Although always arid, northern and central Chile receive more rainfall in El Niño years than in other years, particularly in the austral winter. The 1997–1998 El Niño illustrates this pattern (Fig. 6A). The enhanced precipitation during El Niño is clearer in central than in northern Chile, in part because rain falls so rarely in northern Chile (Allan et al., 1997; Diaz and Pulwarty, 1994; Diaz et al., 2001; Halpert and Ropelewski, 1992; Kiladis and Diaz, 1989; Lau and Sheu, 1991; Serra B., 1987; Waylen and Poveda, 2002). Only in the exceptional El Niño such as 1997–1998 does it rain there at all.

A particularly clear signature of El Niño is shown by the late boreal winter to early spring SSTs (February to April), which correlate with SST anomalies averaged over 5°N–5°S, 172°E–120°W during the preceding November to January (Alexander et al. 2002). Thus, a slight delay separates warming in the tropical Pacific and that farther south. In addition, El Niño years correlate with large rainfall in the austral winter months (June–August) that follow the mature period of El Niño (December–February). For example, Serra B. (1987) reported that during the 1982–1983 El Niño, the SST off Arica in northern Chile was 6 ºC warmer than normal in June 1983, and the thermocline, as defined by the 15 ºC isotherm, was depressed to 150 m in May 1983. Moreover, sea-surface salinity also reached a record-breaking level, 35.8‰, and remained higher than 35.3‰ from 1982 to October 1983. These high values of salinity imply that although temperatures were high, rainfall over the ocean was not; presumably that rain fell on land to the east.

With regard to paleoceanographic estimates of sea-surface temperatures, those based on alkenones in sediment deposited between 3.29 and 2.97 Ma both in the eastern equatorial Pacific (Site 847: 0°N, 95°W) and off the coast of Peru (Site 1237: 16°S, 76°W) were warmer than those today, by 2.7 °C and 5.4 °C, respectively (Haywood et al., 2005). Both are consistent with a warm, El Niño–like early Pliocene climate.

Concerning precipitation, northern Chile seems to have been wetter in late Miocene and early Pliocene time than today. Citing evidence given by Sáez et al. (1999), Chong Díaz et al. (1999), Gaupp et al. (1999), and May et



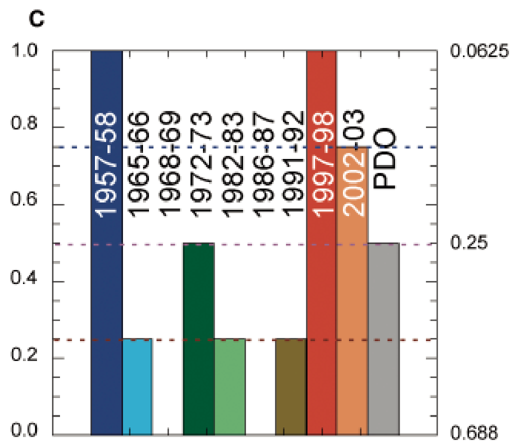


Figure 6. Comparisons of inferred differences between late Miocene-early Pliocene and present-day precipitation from South America with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B) such differences are superimposed on maps (A) of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996 and (B) of correlations of precipitation anomalies between 1949 and 2003 with the Pacific Decadal Oscillation Index. In (C) binary correlations of paleo-precipitation anomalies with El Niño teleconnections are shown for each event. On the right, numbers show probabilities of the fraction of the locations with positive correlations equaling or exceeding the value shown on the left, assuming that the probability obeys a binomial law with probability of agreement or disagreement equaling 0.5.

al. (1999), some of whom argued for different climatic histories, Hartley and Chong (2002) inferred that desiccation in the region from 19.75°S to 23ºS began before 3 Ma, but with much of it since that time (Fig. 6). Although Rech et al. (2006) disagreed with this history of climate change, Allmendinger et al. (2005) and Arancibia et al. (2006) supported Hartley and Chong's (2002) contention; Allmendinger et al. (2005) specifically argued for a moister climate in the segment between 19ºS and 21.6ºS for late Miocene time to ca. 4 Ma, and perhaps 3.49 ± 0.4 Ma, after which aridification occurred.

Recent studies of river incision on the west coast of South America in northern Chile and southern Peru concur with these inferences of late Cenozoic climate change. Workers in both areas have noted increased incision of rivers emanating from the Western Cordillera of the Andes at ca. 10–8 Ma, which most assign to a rise of the Cordillera at that time (e.g., Hoke et al., 2007; Kober et al., 2006; Rech et al., 2006; Schildgen et al., 2007; Schlunegger et al., 2006; von Rotz et al., 2005). Incision rates then decreased since ca. 3 Ma along the western slopes of the Andes at low elevations, where climate is hyperarid today, presumably because of a decreased discharge of water (e.g., Hoke et al., 2007; Kober et al., 2006; Schildgen et al., 2007).

Although opinions on this aridification have been evolving during the past few years, there seems to be consensus about Pliocene aridification, which is consistent with a shift from El Niño–like conditions from before ca. 3–4 Ma to a more arid present-day climate.

Numerous studies have demonstrated that rainfall increases in southern Brazil and southeastern Argentina in austral spring and summer (October–January) during El Niño (Coelho et al., 2002; Diaz et al., 2001; Grimm et al., 2000;

Halpert and Ropelewski, 1992; Lau and Sheu, 1991; Mason and Goddard, 2001; Ropelewski and Halpert, 1987, 1996) and decreases during La Niña (Mason and Goddard, 2001; Ropelewski and Halpert, 1989, 1996). This is one of the more robust ENSO correlations and is illustrated well by the 1997–1998 El Niño (Fig. 6A).

Study of late Miocene or early Pliocene paleoclimates of this region seems to be limited to that of Zarate and Fasana (1989), who stated (p. 27), "Vertebrate fossil assemblages document warm and wetter Pliocene and Early Pleistocene climate" for the central eastern Pampas, or the Buenos Aires Province, Argentina.

The paleoclimate data from each part of South America for which we have data are rendered dubious for a different reason. First, the argument that in late Miocene-early Pliocene time the Amazon Basin was relatively arid comes in large part from sediment deposited in the eastern Pacific (Hovan, 1995), and pinpointing the arid region (thousands of kilometers away) is impossible. Moreover, the inference that eastern Argentina was wetter at that time is hardly definitive, for the dating is imprecise and the argument is qualitative. Thus, of the four paleoclimate data (Table 2), we could question two of them, and the other two come from overlapping areas.

Nearly all El Niño events are associated with markedly decreased precipitation over the Amazon Basin. Only two do not show this; for the 1986–1987 and 1991–1992 El Niño events, rainfall there was higher than average. Also, rainfall correlates positively with the PDO index (excess precipitation for positive PDO index) (Fig. 6B), and hence is opposite to the typical correlation for El Niño or the Niño 3.4 index, for instance. Thus, these observations suggest that the SST anomalies associated with these two El Niño events and with the PDO may not accurately portray a pre–Ice Age prototypical Pacific SST distribution. (We note without further comment that one feature shared by the 1986–1987, but not the 1991–1992, SST distribution and the PDO is the wide region of warmth north of the equator in the eastern Pacific.)

The 1997–1998 El Niño correlates best with paleoclimate differences (Fig. 6C), and although not shown, this holds whether the Amazon Basin is included or not. Although it does not influence the correlation coefficient that we calculate, 1997–1998 brought greater precipitation in northern Chile than other El Niño events.

Western Europe

On average, ENSO teleconnections to Europe are not strong (e.g., Kiladis and Diaz, 1989; Ropelewski and Halpert, 1987; van Oldenborgh and Burgers, 2005), but they seem to be present. For temperature, Kiladis and Diaz (1989) reported a slight cooling (–0.3 °C) in Madrid, Spain during September–November of El Niño years and a slight warming (0.4 °C) during La Niña years. During the 1997–1998 El Niño, however, much of Europe warmed (Fig. 7A). Similarly, temperatures over much of southern Europe and the western Mediterranean region correlate positively with the Pacific Decadal Oscillation index (Fig. 7B). Toniazzo and Scaife (2006) reported that the strength of ENSO teleconnections to the North Atlantic and Europe depends nonlinearly on the strength of sea-surface temperature anomaly in the eastern Pacific. Strong El Niño events affect sea level pressures and related climatic quantities disproportionately more strongly than weak El Niño events.

For precipitation, much of the Iberian Peninsula and neighboring regions receive less rain during strong La Niña years than normal, and although teleconnections are weaker, some El Niño events are associated with excess rainfall (Kiladis and Diaz, 1989; Pozo-Vázquez et al., 2005; Rodó et al., 1997; Vicente-Serrano, 2005). Pozo-Vázquez et al. (2005), for instance, showed that that winter rainfall is less than normal during La Niña, with differences reaching 20% in the southwestern Iberian Peninsula, and Rodó et al. (1997) reported more rainfall in eastern Spain during El Niño years. The correlation of Pozo-Vázquez et al. (2005) applies to the entire Mediterranean region, from Iberia to the Anatolian peninsula. Although Pozo-Vázquez et al. (2005) reported that the strength of the rainfall in southwestern Europe does not correlate with the strength of the ENSO events, the 1997–1998 El Niño was associated with more winter rain over southwestern Europe than normal, if less in northeastern Spain than suggested by the correlation reported by Rodó et al. (1997) (Fig. 8). During the relatively large 1998–1999 La Niña, less rain fell than normal (Dong et al., 2000). Finally, consistent with Toniazzo and Scaife's (2006) observation that strong El Niño events have a stronger impact on Europe than weak events, Dong et al. (2000) replicated the general form of precipitation anomalies over all of western Europe in both the 1997–1998 El Niño and the 1998–1999 La Niña using a General Circulation Model (GCM) forced by the appropriate equatorial Pacific SSTs.

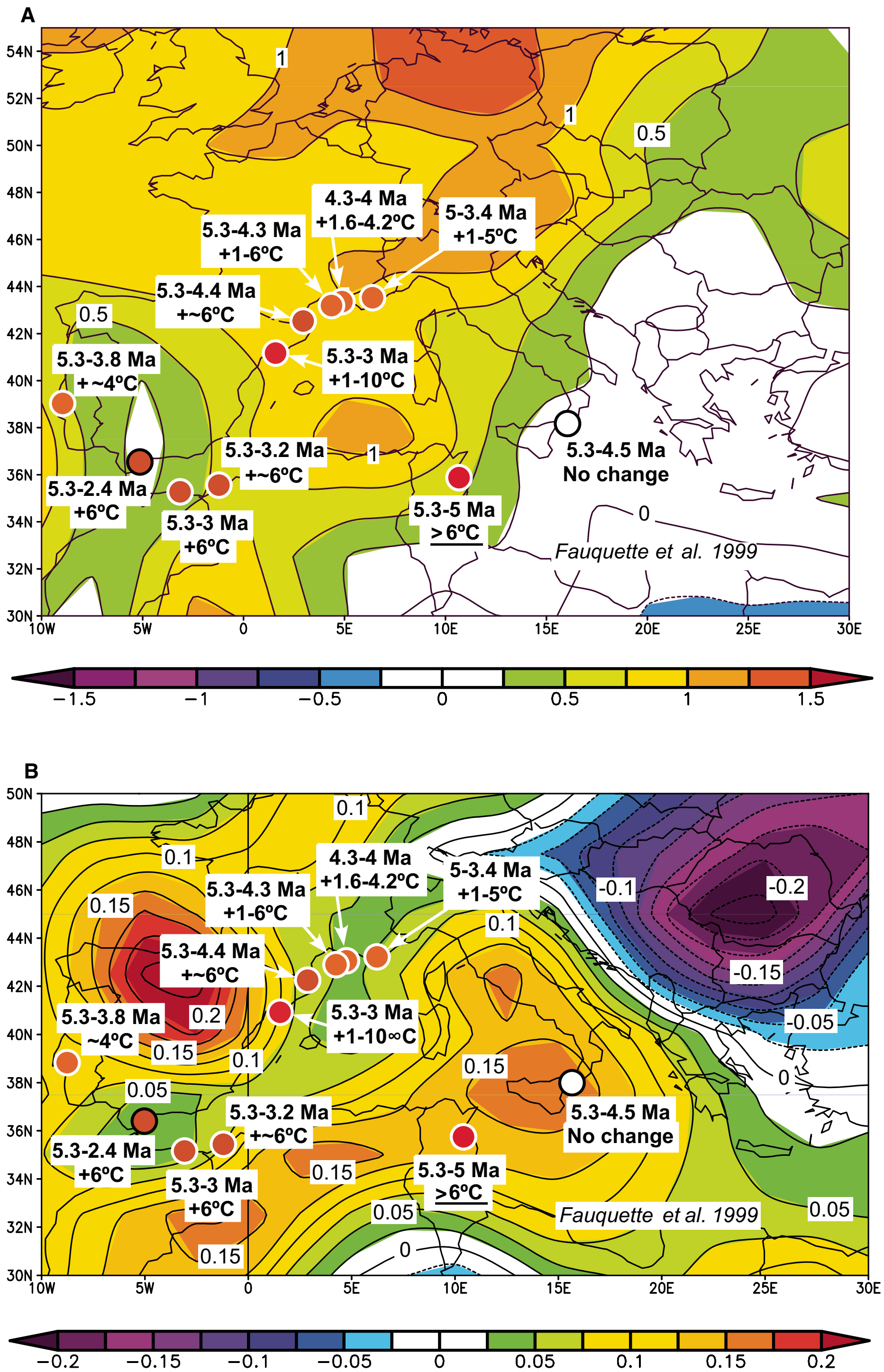
Early Pliocene climates in the Mediterranean region seem to have been warmer than today. Thus, they are not in agreement with the El Niño-La Niña difference reported by Kiladis and Diaz (1989), but they are consistent with the enhanced warmth in 1997–1998. Moreover, the Mediterranean region seems to have been wetter than today, a pattern that does resemble more El Niño than La Niña present-day teleconnections. In particular, using pollen assemblages, Fauquette et al. (1999) inferred that climates of Portugal were warmer by ~4 °C than today and that precipitation exceeded that of today by 400 mm/yr (Figs. 7 and 8). Similarly, for Andalusia in southern Spain, differences were a few degrees Celsius and 100–300 mm/yr. In Catalonia in northeastern Spain, Fauquette et al. (1998, 1999) inferred that between 4.5 and 3.6 Ma, air was warmer by 1–10 °C than today and precipitation was ~600 mm/yr more than at present. They reported similar differences from a number of sites in southern France, with differences diminishing toward the east in Sicily (Fauquette et al., 1999; Suc, 1984). By contrast, North Africa from Morocco to Tunisia seems to have been both warmer and drier than today (Figs. 7 and 8). Thus, although the canonical El Niño response in southern Europe is subtle at best, that associated with the strong El Niño of 1997–1998 qualitatively resembles the difference between paleo- and present-day climates, if better for temperature than for precipitation. The poorer correlation for precipitation surely results in part from the various sites studied by Fauquette et al. (1998, 1999) lying along boundaries between positive and negative precipitation anomalies.

Early Pliocene temperature differences from present-day averages correlate positively with El Niño teleconnections for most years (Fig. 7C). The high correlations for El Niño events since 1980 might reflect global warming, independent of El Niño. In any case, the 1986–1987 and 1997–1998 El Niño events show the highest correlations.

We explored correlations of El Niño and the PDO teleconnections with inferred precipitation anomalies in southern Europe and western North Africa (Fig. 8). In nearly all cases, correlations were negative or only slightly positive (e.g., 1968–1969). As noted above, we associate the poor correlations, at least in part, with the paleoclimate observations coming from localities near the boundary between heavier and lighter rainfall during El Niño events. Thus, we pursue these correlations no further.

West Coast of Africa in the North Atlantic

Halpert and Ropelewski (1992) showed that during El Niño years the west coast of Africa warms (see also Saravanan and Chang (2000)). Weakened trade winds blowing parallel to the coast reduce coastal upwelling of cold deep water (Roy and Reason, 2001; Zhang et al., 1997). Using a "Multivariate ENSO Index" for El Niño, Roy and Reason (2001) not only



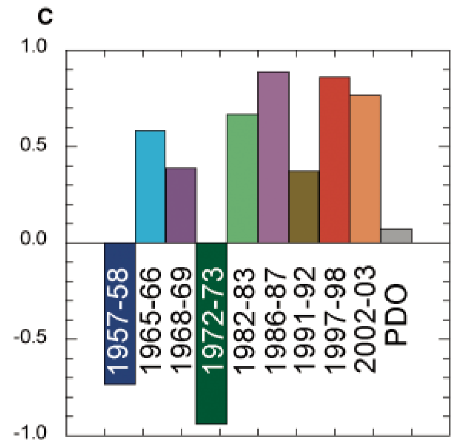


Figure 7. Comparisons of inferred differences between late Miocene-early Pliocene and present-day temperatures from Western Europe and North Africa with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B), such differences are superimposed on maps (A) of temperature anomalies for the period May 1997 to April 1998, compared with the average for the period 1968–1996 and (B) of temperatures between 1949 and 2003 regressed on the Pacific Decadal Oscillation Index. In (C) correlations of paleo-temperature anomalies with El Niño teleconnections are shown for each event.

showed weakened trade winds, but also confirmed a weakening of upwelling of cold deep water by showing a correlation of sea-surface temperature anomalies with their ENSO index. They used their empirical results to predict a warming of ~1 °C during the 1997–1998 El Niño, which was observed (Fig. 9). Zhang et al. (1997) showed an opposite correlation with the Pacific Decadal Oscillation, suggesting that the response of winds off West Africa to warming in the eastern equatorial Pacific is sensitive to the distribution of warming.

Paleoclimatic and paleoceanographic records suggest a strengthening of the trade winds near 3.2 Ma, perhaps with a cooling and drying of the coast occurring a little earlier at 3.5 Ma (Dupont and Leroy, 1999; Leroy and Dupont, 1994, 1997). Using alkenone paleothermometry, Herbert and Schuffert (1998) reported an essentially constant SST of 26.5 °C from 6.5 to ca. 4 Ma, and then, despite large amplitude variations between 4 and 2.2 Ma, the mean SST dropped toward ~23 °C. Pollen provides additional evidence by suggesting the northern edge of mangrove swamps in early Pliocene time lay 5° north of its present position Ma (Dupont and Leroy, 1999; Leroy and Dupont, 1994, 1997). In addition, the composition of sediment deposited offshore (20°45′N; 18°35’W) shows little silt and abundant clay between 3.7 and 3.1 Ma, from which Leroy and Dupont (1997) inferred more runoff than now, as a result of weaker easterly trade winds. They reported that after this interval, dust deposition increased, suggesting an aridification of the region to the east. Leroy and Dupont (1994) inferred that the transition from a wetter period with weak trade winds occurred gradually, between 3.245 Ma and 2.609 Ma. The shift between ca. 3.5 and ca. 2 Ma, from a wetter and warmer climate presumably with weak easterly trade winds, concurs with a shift from an El Niño–like climate, with weak trade

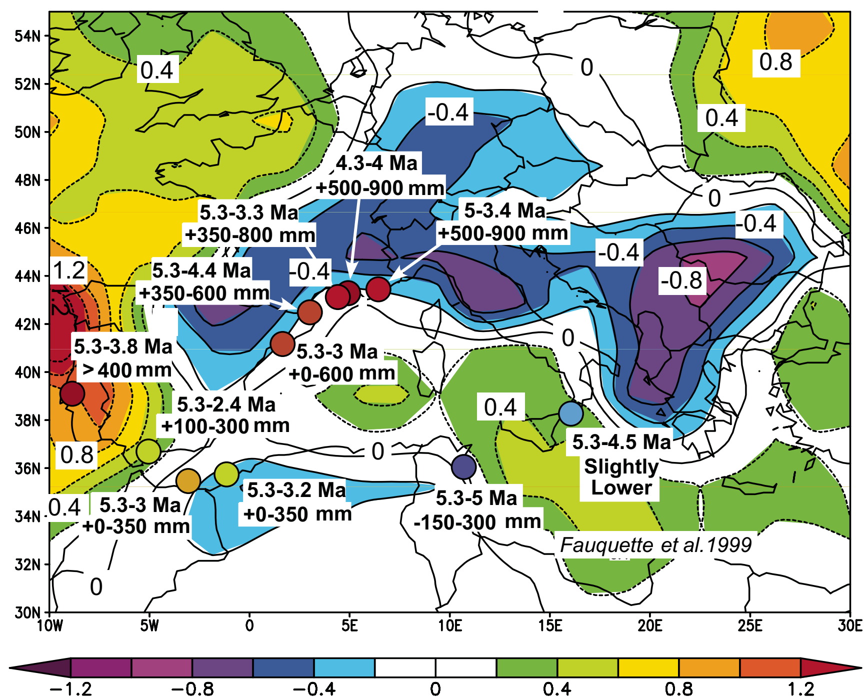


Figure 8. Comparisons of inferred differences between late Miocene-early Pliocene and present-day precipitation from Western Europe and North Africa, superimposed on a map of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996.

winds and warm SSTs to the more common lower SSTs and strong easterly trade winds.

With only one quantitative paleoclimatic observation, seeking correlations seems unlikely to be revealing, but because the 1997–1998 El Niño was associated with the largest SST anomaly, we carry out a simple analysis. We arbitrarily assume that Dupont and Leroy's (1999; Leroy and Dupont, 1994, 1997) observations imply an SST warmer by 1 °C than today. Then with two data, not surprisingly, the 1997–1998 El Niño event correlates best, but no pattern appears among the others that do or do not correlate well (Fig. 9B).

Central Africa (Chad)

Definitive evidence showing teleconnections with Central Africa, southeast of the Sahara, and specifically to Chad and its surroundings, does not seem to exist. In Figure 4.2 of Dettinger et al. (2000), which shows anomalies in rainfall between October to September rainfall for selected El Niño (1982–1983, 1986–1987, 1991–1991, and 1994–1995) and selected La Niña events (1983–1984, 1984–1985, and 1988–1989), the Sahel appears to have been slightly wetter than normal in El Niño. Dettinger et al. (2000) did not discuss this apparent correlation, and their figures also did not show the opposite correlation with La Niña events. By contrast, Janicot et al. (1996) reported that precipitation in the Sahel decreased with warming of the eastern Pacific. Our analysis of NCEP reanalysis (Kalnay et al. 1996) shows no correlation with Southern Oscillation Index and no precipitation anomaly in 1997–1998. Nevertheless, we discuss this area because pre–Ice Age climates differed from those of today.

Several observations indicate perennial lakes and aquatic habitats between roughly 7 and 3 Ma and suggest therefore that the area

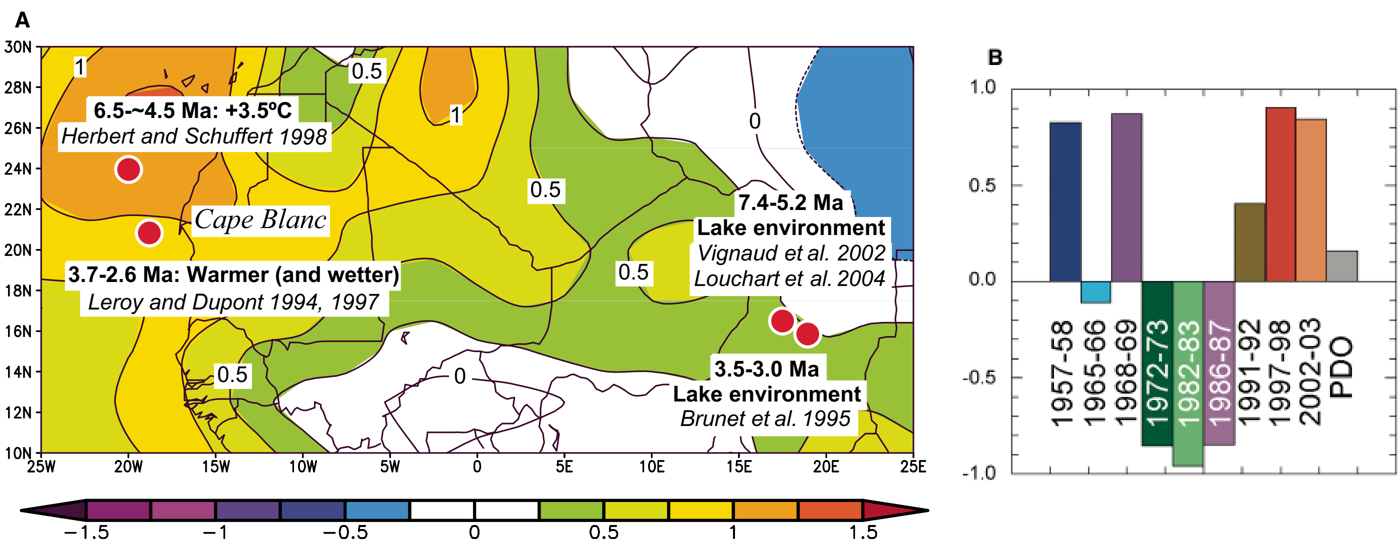


Figure 9. Comparisons of inferred differences between late Miocene-early Pliocene and present-day temperatures from west and central Africa with that associated with El Niño events. (A) Such differences are superimposed on a map of temperature anomalies for the period May 1997 to April 1998, compared with the average for the period 1968–1996. (B) Correlations of early Pliocene sea-surface temperature anomalies with El Niño teleconnections are shown for each event.

was wetter than today (Fig. 9A). In particular, fossil fish, crocodiles, and amphibious mammals indicate the presence of lakes, as far back as 5.2–7.4 Ma (Vignaud et al., 2002), though Vignaud et al. (2002) did note that deserts were not necessarily far away. Fossils of other aquatic taxa (Brunet et al., 1995), including birds whose modern relatives live near lakes (Louchart et al., 2004), suggest the presence of lakes between 3.5 and 3.0 Ma. Similarly, plant fossils suggest forests near lakes and streams ("gallery forest") at this time (Duringer et al., 2000).

Because of the poor correlation of precipitation with El Niño events, this evidence for a wetter Chad than at present tells us little about El Niño. The wetness in Chad most likely had a different cause.

West Coast of Africa in the South Atlantic: The Benguela Current

Correlations of modern variability in SST anomalies, wind stress anomalies, and precipitation over southwest Africa with measures of El Niño are less clear than over northwest Africa, if any correlation exists at all. Were this area not characterized by a particularly large difference between present-day and pre–Ice Age sea-surface temperatures and precipitation, we might not discuss it at all.

Zhang et al. (1997) showed in their Figures 11 and 12 (but did not discuss) a weakening of the easterly trade winds over the eastern South Atlantic both for El Niño phases of ENSO and for positive phases of the Pacific Decadal Oscillation. (We found no other mention of such correlations.) The correlation with the Pacific Decadal Oscillation may be the more robust signal, but few are likely to find it overwhelming. The pattern described by Zhang et al. (1997) could not include the 1997–1998 El Niño, and, in fact, including it eliminates any obvious correlation in the South Atlantic with El Niño. Moreover, the study by Enfield and Mayer (1997), which used a slightly different index for ENSO, shows a correlation, if also not very significant, opposite to that in Figures 11 and 12 of Zhang et al. (1997). Enfield and Mayer (1997) showed a positive correlation of wind speeds off the coast of Namibia with the El Niño index that they used and a corresponding positive correlation of SSTs with it, but their correlations are delayed and seem to apply to the boreal spring and summer following the mature El Niño phase in boreal winter. This delay makes the patterns similar to those discussed by Roy and Reason (2001) for the west coast of Africa in the North Atlantic. More similar to the study of Zhang et al. (1997), Alexander et al. (2002) showed that SST anomalies in the Pacific averaged over 5°N–5°S, 172°E–120°W (another ENSO index) in November to January correlate positively with SST anomalies in the following February to April off the west coast of South Africa a few degrees south of the Namibian coast. Although they did not discuss this region specifically, they implicitly concluded that the link between El Niño and the SST anomalies is through an altered pressure gradient in the atmosphere over the South Atlantic and its effect on wind stress, not to perturbations in large-scale ocean circulation in the South Atlantic. Thus, their results suggest a correlation with El Niño, at least by the measure they used to define it. Consistent with the hint of a correlation with the Pacific Decadal Oscillation and the differences among studies employing different indices for El Niño, the connection between eastern equatorial Pacific SSTs and variability in the South Atlantic may be less direct than most teleconnections (Carton and Huang, 1994; Delecluse et al., 1994; Florenchie et al., 2003, 2004; Hirst and Hastenrath, 1983).

One of the strongest signals of late Pliocene climate change comes from the South Atlantic, along the coast of Namibia. Using alkenones to infer a record of surface temperatures since 4.5 Ma, Marlow et al. (2000) reported a huge drop of ~10 °C off the coast of Namibia beginning at 3.2 Ma (or 8.9 °C, according to Haywood et al. (2005)). They showed a gradual cooling beginning near 4 Ma with an accelerating rate of cooling until ca. 1 Ma. Because wind-driven upwelling now brings cold water up to the surface, they associated the change in SST with a change in winds. Analyses of diatoms (Dowsett, 1989) and pollen (Dowsett and Willard, 1996) offshore of Namibia concur with such a change in the Benguela current.

The colder water along the coast and offshore seems to be associated with more arid conditions inland. Segalen et al. (2002) reported a shift in $\delta^{13}C$ in eggshells near ca. 3.5 Ma, which they interpreted as a shift toward diets more dependent on C4 plants. As seasonally arid climates favor C4 plants, this shift might reflect an aridification of southwest Africa. Scott (1995) also inferred an aridification of southwest Africa from changes in pollen, though Van Zinderen Bakker and Mercer (1986) suggested that Namibia was already hyperarid by late Miocene (ca. 10–9 Ma). Van Zinderen Bakker and Mercer (1986) had attributed that hyperaridity to a strong, cold Benguela current since that time, but the work of Marlow et al. (2000) renders their inferred timing too early.

The study by Marlow et al. (2000) demonstrates a large change concurrent with the shift from warm equable climates in the Northern Hemisphere to recurring ice sheets in Canada and Fennoscandia. Surely, atmospheric or ocean dynamics link them, and if not definitive, the correlations shown by Alexander et al. (2002) and by Zhang et al. (1997) for different indices, as well as links to tropical ocean circulation (Carton and Huang, 1994; Delecluse et al., 1994; Florenchie et al., 2003, 2004; Hirst and Hastenrath, 1983), allow for the possibility of a connection; however, the evidence is far from compelling.

East Africa

Many studies have reported greater rainfall in East Africa during El Niño than during La Niña (Curtis and Adler, 2003; Dai et al., 1997; Diaz et al., 2001; Lau and Sheu, 1991; Reason et al., 2000; Ropelewski and Halpert, 1987, 1996) (Fig. 10A). The GCM study of Goddard and Graham (1999) makes a convincing case that the direct influence of the El Niño SST anomalies in the Pacific is to reduce rainfall, and that the observed correlation is a consequence of the warming of the western Indian Ocean that also usually accompanies an El Niño event. (Also see Barsugli and Sardeshmukh, 2002.) Thus, the state of east African rainfall in the pre–Ice Age world is more an indication of the state of the Indian Ocean than of the Pacific. We also note that the correlation with the Pacific Decadal Oscillation seems to be opposite to that of typical El Niño years (Fig. 10B).

The spatial pattern of the East African connection to ENSO is complex. In the northern part of this region, rainfall correlates with El Niño, but farther north, it anticorrelates, manifesting itself, for instance, by lower discharge of the Nile (e.g., Grove, 1998; Grove and Chappell, 2000; Quinn, 1992). In the south, however, the correlation is weak, or negative, with decreased rainfall during El Niño events.

The paleoclimate record for East Africa demonstrates clearly that in late Miocene and early Pliocene time most of this area was wetter than today (e.g., Hamilton and Taylor, 1991; Hill, 1995; Leakey et al., 1996). The transition from moist to arid climates seems to have occurred first in the equatorial part of East Africa and later in Ethiopia (Fig. 10) (Cane and Molnar, 2001).

From Lake Tana, 12.6°N, 37.1ºE, pollen deposited in a lacustrine environment since ca. 8 Ma (but without a precise younger limit) show "abundant wet lowland rainforest taxa and pteridophytes, a very weak representation of grasses, and a total absence of conifers," all of which indicates a warm humid climate (Yemane et al., 1985).

Some pollen, among approximately one hundred taxa, from Hadar, Ethiopia (11.1°N, 40.6°E), indicate aquatic plants and abundant grass apparently near lakes at 3.2–3.6 Ma, but with others suggesting nearby forests, if with fewer trees than before; both lakeside environments and forests differ markedly from the desert conditions of this region today (Bonnefille, 1984, 1995). Bonnefille et al. (1987), in fact, inferred an annual rainfall of 800–1000 mm in early Pliocene time, compared with less than 400 mm today. They reported that extensive grassland, and more arid conditions, "certainly" with <800 mm/yr of rain followed, so that by 2.9 Ma, evergreen bushland and montane forest again extended to a lakeside. Although a more humid climate followed, it was not as humid as it had been at 3.3 Ma, but still much more so than today. Consistent with these reports, Quade et al. (2004) inferred from carbon-13 isotopes that before 2.92 Ma, C3 plants were widespread (64%), but afterward, C4 grasses dominated, suggesting either more seasonal climates or greater aridity.

Farther south, in the Middle Awash Valley (10.3°N; Fig. 10), evidence of a moist climate in pre–Ice Age time includes a fossil hippopotamus dated to the interval 5.2–4.9 Ma, which Boisserie (2004) used to buttress other observations suggestive of "a wet and relatively wooded environment." Such an environment seems to have prevailed at 5.77 Ma to 5.54 Ma (WoldeGabriel et al., 2001) and at 4.4 Ma (WoldeGabriel et al., 1994); evidence for forests includes a variety of fauna (monkeys and bats, for instance) and also fossil plant remains, such as seeds. Later, at 2.5 Ma, fluvial deposits on flood plains and deltas containing fossils of grazing mammals suggest a broad grassy plain adjacent to a lakeside or riverine environment (de Heinzelin et al., 1999).

At Gadeb, Ethiopia (7°N, 39°E), pollen from Ericaceous grasslands dated at 2.35–2.5 Ma suggests cooler and drier environments than both today and earlier (Bonnefille, 1983, 1984). Bonnefille (1995) later reported a drop of 5–6 °C in temperature at this time in this region.

Farther south, in southern Ethiopia in the Omo-Turkana Basin, pollen dated at 3.55 Ma to 4.1 Ma and fossil wood indicating deciduous woodland suggest a wetter climate than today, and younger pollen, deposited between 3.7 and 3.2 Ma, suggests that rain forest conditions prevailed (Bonnefille, 1995). Consistent with this image, Williamson (1985) described a fruit

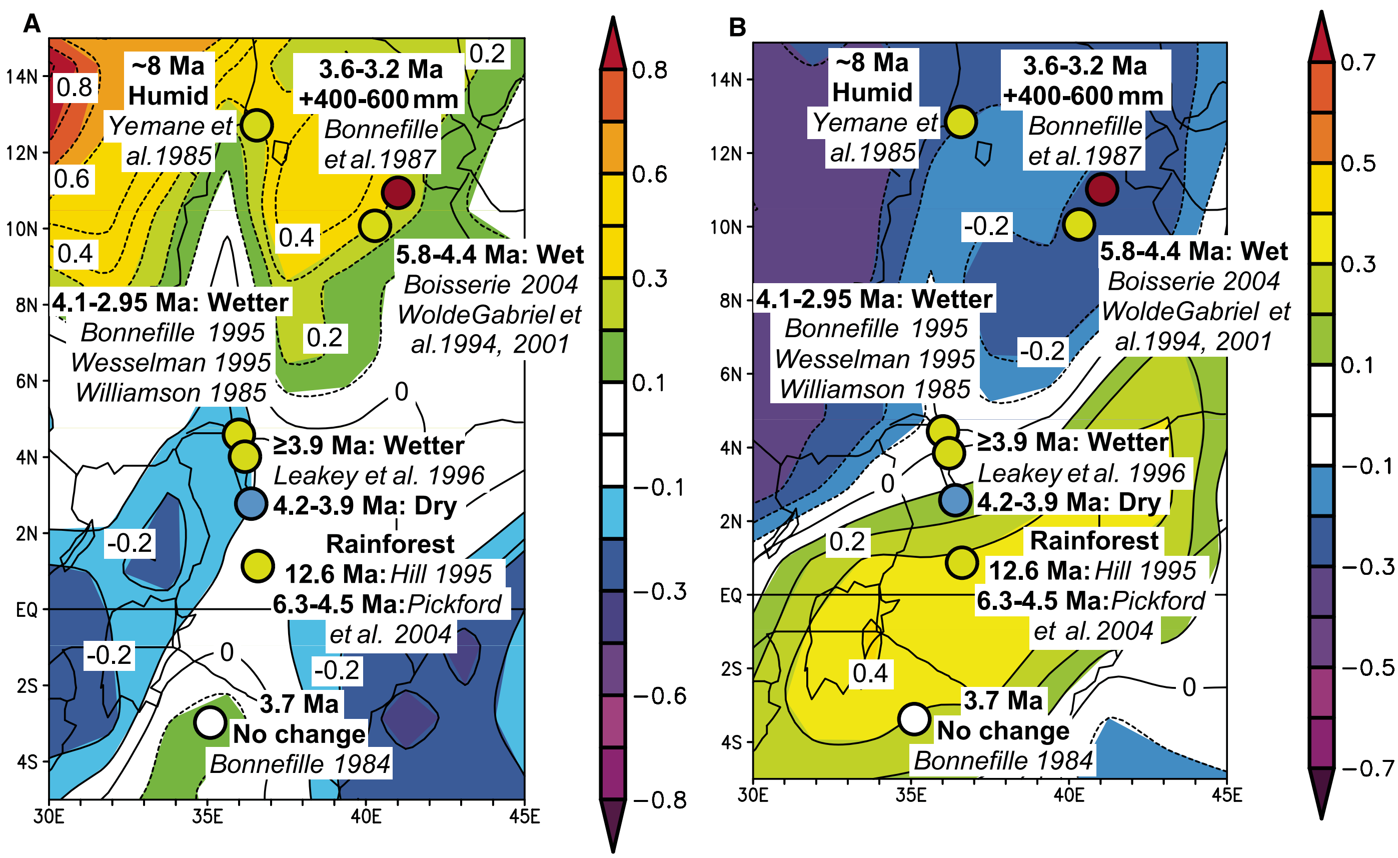


Figure 10. Comparisons of inferred differences between late Miocene-early Pliocene and present-day precipitation from East Africa with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). (A) Such differences are superimposed on a map of composite precipitation anomalies (in mm/day) from the East Africa for the nine El Niño years, 1957–1958, 1965–1966, 1968–1969, 1972–1973, 1982–1983, 1986–1987, 1991–1992, 1997–1998, and 2002–1903, each covering the twelve months from May of the first year to April of the second, and referenced against the mean monthly anomalies between 1968 and 1996. (B) Differences between late Miocene-early Pliocene and present-day precipitation from East Africa are superimposed on a map of correlations of precipitation anomalies between 1949 and 2003 with the Pacific Decadal Oscillation Index of Mantua et al. (1997).

and a gastropod, both of which suggest a rain forest environment at 3.3–3.4 Ma. Moreover, Wesselman (1995) reported that at 2.95 Ma, fossils of small mammals were represented by those characteristic of tropical forests and mesic woodlands, including "species characteristic of the equatorial high forests of Central and West Africa," but by a little before 2.52 Ma, the tropical forest was represented by only one species (in fact, a "forest-edge taxon"), and mesic woodlands dominated. He stated that by 2.34 Ma, riverine and forest taxa had diminished, and xeric species dominated, and then, just after 2.32 Ma, forest taxa were gone; only "Dry savannas/open savanna woodland" and "Arid semiarid steppe" taxa comprise the fossil record (Wesselman, 1995).

Leakey et al. (1996) reported for the area farther south (Fig. 10) "a transition from earlier Miocene forest ecosystems to Plio-Pleistocene savanna-mosaic ecosystems." The evidence for the wetter Miocene environment comes largely from fossil fauna: fish, oyster, crocodile, hippopotamus, rodents, impala, etc. Although Leakey et al. (1995) inferred a gallery forest at 3.9 Ma for Allia Bay ~4°N, 36ºE in northern Kenya, where the present climate is arid, farther south at Kanapoi 2.3°N, 36.1ºE, they described "dry, possibly open, wooded or bushland conditions" from the micro- and macro-fauna dated at 3.9–4.2 Ma, though they allow for a "wide gallery forest." Bonnefille (1984) reported a marked decrease in trees and an increase in grass at ca. 1.9 Ma from East Turkana, Kenya, suggesting increased aridity.

Farther south in the Baringo district, just north of the equator in Kenya (Fig. 10), Hill (1995) reported a rich floral assemblage with fifty-five species of trees and lots of leaves. Those dating from 12.59 Ma indicate a "lowland rain-forest habitat," and fossil wood at ca. 6.5 Ma suggests that savannas had not yet taken over. From fossil mammals found in largely lacustrine sedimentary units dated between 6.2 ± 0.19 Ma and 5.65 ± 0.07 Ma in the Tugen Hills, west of Lake Baringo, Kenya (0°45′N to 1°30′N, 35°50′E to 36°E), Pickford and Senut (2001) concluded: "The predominance of impalas in the Kapsomin faunal assemblage suggests that the surroundings of the site were probably open woodland, while the presence of several specimens of colobus monkeys indicate that there were denser stands of trees in the vicinity, possibly fringing the lake margin and streams that drained into the lake." Subsequent work on younger material, however, implies that rainforests persisted into Pliocene time: "The Early Pliocene Mabaget Formation (5.3–4.5 Ma), Tugen Hills, Kenya, has yielded remains of the African tragulid *Hyemoschus aquaticus*, which is today confined to rainforests of West Africa and the Congo Basin as far east as western Uganda" (Pickford et al., 2004, p. 179). Pickford et al. (2004) also described paleosols with dark brown to black, iron-rich, almost lateritic horizons that imply a tropical humid environment. "All this evidence suggests that the Tugen Hills region was considerably more humid and far less seasonal from 6.3 to 4.5 Ma than it is today, and that it was probably covered in tropical rain forest" (Pickford et al., 2004, p. 186). Thus, aridification seems to have begun at this time, if the climate was not yet as arid as today.

Finally, pollen from Olduvai, Tanzania (Fig. 10) suggest mostly a wooded grassland, although "fluctuating through time, montane forest" was present some of the time near 1.8 Ma (Bonnefille, 1984). Farther south, at Laetoli, Tanzania (3.2°S, 35.2°E), Bonnefille (1984) reported pollen suggesting a "wooded grassland with a montane forest a few kilometers away" at 3.7 Ma that is similar to the present-day environment.

Taken together, these observations suggest that East Africa has become arid during the past few million years, with the transition beginning first in the south, and reaching farther north most recently (Fig. 10). The complex spatial pattern of correlations between present precipitation and El Niño and the evidence for a more direct impact of sea-surface temperatures in the Indian Ocean deny the paleoclimatic record from East Africa much weight in assessing the distribution of sea-surface temperatures in the pre–Ice Age eastern equatorial Pacific.

The Indian Subcontinent

Data for longer than a century have shown a negative correlation between Indian Monsoon rainfall (and hence annual rainfall) and El Niño events (Charles et al., 1997; Diaz et al., 2001; Klein et al., 1999; Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987, 1996). Catastrophic monsoon failures, as in 1790 (Grove, 1998) and 1877–1878 (Charles et al., 1997; Davis, 2001; Kiladis and Diaz, 1986; Nicholls, 1991), coincide with major El Niño events. Goswami and Xavier (2005) suggested that this correlation exists because ENSO affects the duration of the monsoon season, not the intensity of rain.

This correlation seemed to have broken down for the ~25-yr interval between ~1976 and 2000 (e.g., Ashok et al., 2001; Kinter et al., 2002; Krishna Kumar et al., 1999; Miyakoda et al., 2003; Pfeiffer et al., 2004). The period from 1976 to 2000 includes the two largest El Niño events of the twentieth century, those in 1982–1983 (a below average monsoon year) and in 1997–1998 (a normal monsoon; Fig. 11). The 2002–2003 El Niño, however, was associated with a notably weak monsoon (Cane, 2005; Gadgil et al., 2003). Allowing for the influence of the sea-surface temperature distribution in the Indian Ocean helps account for the imperfect correlation between El Niño indices and monsoon strength (e.g., Ihara et al., 2007). Another suggested explanation for that poor correlation includes the eastward displacement of both the center of convection over the western Pacific and the locus of most weakened ascent over the Indian Ocean and Asia, eastward shifts in the Walker Circulation, during El Niño events (e.g., Kawamura, 1998; Kawamura et al., 2004; Krishna Kumar et al., 1999, 2006). Whereas during most El Niño events, descent in the upper troposphere is reduced over India, in some El Niño events, including some unusually strong events such as 1997–1998, the locus of anomalous descent lies farther east. Krishna Kumar et al. (2006) showed that the degree to which El Niño affects the Indian monsoon depends on the locus of anomalously high sea-surface temperature in the western Pacific. When the maximum SST anomaly lies in the central Pacific near the dateline, the Indian monsoon is weak, but if the maximum SST anomaly lies farther east (Fig. 1), then the monsoon is normal or near normal. Stockdale et al. (1998), in fact, showed that a General Circulation Model forced with the anomalous 1997–1998 tropical Pacific SST distribution associated with that El Niño called for only slightly less rainfall than normal over India, not the commonly observed large difference.

The relationship of El Niño to the Indian Monsoon differs both for different parts of India and for different timing of El Niño events. For those that begin early, anomalies are more likely to have moved to the east by the start of the monsoon season and rainfall is normal (Ihara et al., 2007). Perhaps more important, some parts of India seem to be more sensitive to El Niño than others. Ihara (2007) showed that monsoon rainfall in northeastern India does not correlate significantly with El Niño occurrences, and that in north central India, near the Himalaya, does so only in June, near the beginning of the monsoon.

The few paleoclimate observations we found suggest that northern India was warmer and less arid in early Pliocene time than it is now, but all were obtained where a correlation with El Niño is weak (Ihara, 2007) (Fig. 11). For instance, Gaur and Chopra (1984) reported a change from a warm and humid wooded grassland in northern India to dominantly relatively arid but less warm grassland at ca. 2.7 Ma. (We corrected their date to reflect revisions of the timing of the Gauss/Matuyama boundary.) Nearby, Sanyal et al. (2004) used $\delta^{13}C$ to infer the fraction

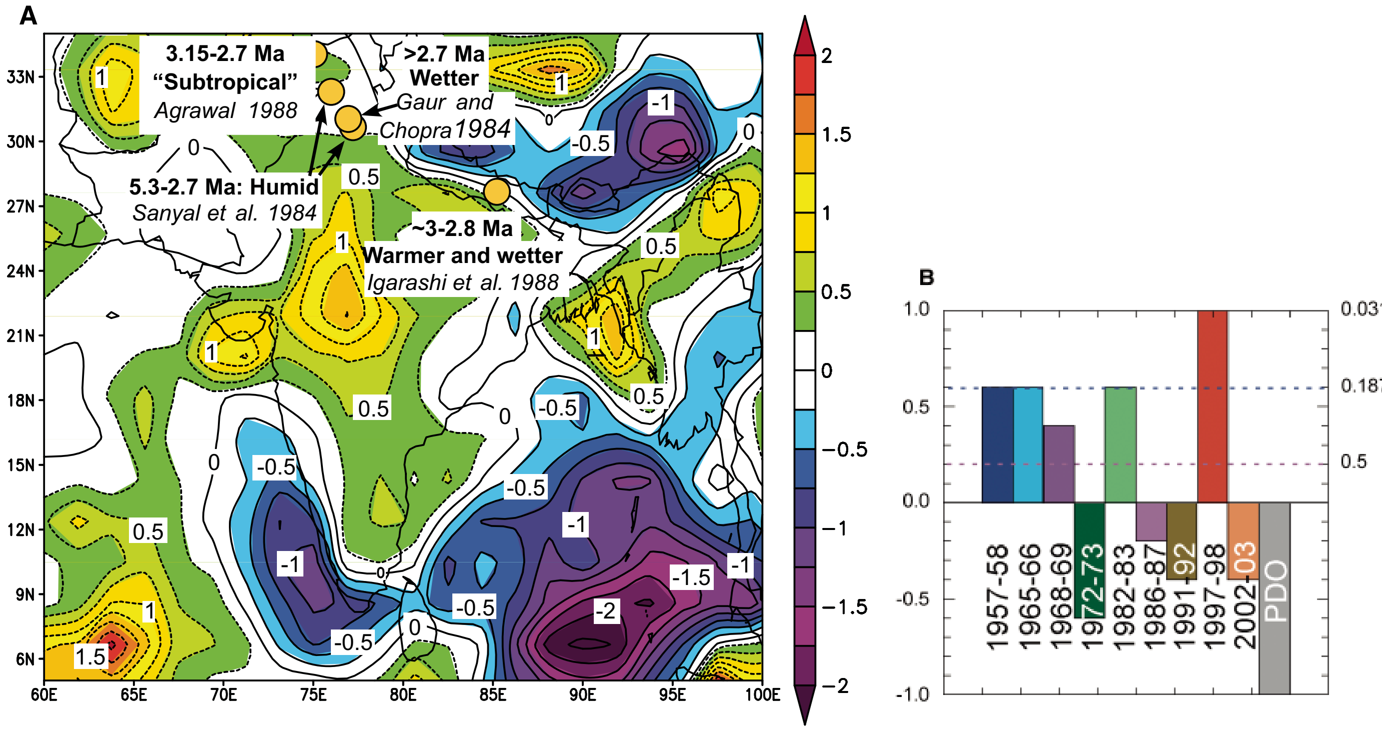


Figure 11. Comparisons of inferred differences between early Pliocene and present-day precipitation from the Indian subcontinent with that associated with El Niño events. (A) Such differences are superimposed on a map of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996. (B) Binary correlations of paleo-precipitation anomalies with El Niño teleconnections are shown for each event. On the right, numbers show probabilities of the fraction of the locations with positive correlations equaling or exceeding the value shown on the left, assuming that the probability obeys a binomial law with probability of agreement or disagreement equaling 0.5.

of vegetation that uses the C4 pathway, which often is associated with seasonally dry climates. They suggested that the monsoon was well established at 10.5 Ma, an inference supported by variations in $\delta^{13}C$ in shells (Dettman et al., 2001) and in equid teeth (Nelson, 2005). Sanyal et al. (2004) inferred that a warm and humid climate prevailed from 5.3 to 2.7 Ma, and then since 2.7 Ma it became cooler and more arid. They suggested the monsoon strength rose to a peak near 5.5 Ma and has subsequently declined. Farther north from Kashmir, Agrawal (1988) reported fossil pollen that suggests a subtropical climate at ca. 3.15 Ma and ca. 2.7 Ma, followed by progressive cooling. Finally, from pollen in the Kathmandu Valley of Nepal, Igarashi et al. (1988) also inferred a cooling since ca. 3 Ma and perhaps drying (based on the increase in *Picea*), but with much variability.

None of these observations provides strong evidence for an early Pliocene climate different from the present-day climate, especially because none comes from the areas of India where the monsoon is most clearly and strongly affected by El Niño. Nevertheless, these observations suggest a warming and drying, and hence are inconsistent with a shift in conditions from those more like El Niño teleconnections to less like them, at least insofar as the observations of paleoclimate apply to more of India than just the north. Conversely, if the early Pliocene climate resembled a strong El Niño, like that in 1997–1998 (Fig. 11), there would be no inconsistency.

Because the only data that bear on pre–Ice Age climate that we have found do not sample well the canonical monsoon or where it is most sensitive to El Niño, a comparison of the few inferences of pre–Ice Age climates that we have found (Fig. 11A) with El Niño teleconnections is risky and could be misleading. Proceeding, we note that in contrast to the weak monsoon-El Niño relation typical of the past century and a half, the 1957–1958, 1965–1966, 1968–1969, 1982–1983, and 1997–1998 El Niños were associated with higher than normal rainfall in the areas for which paleo-precipitation has been studied (Fig. 11B). As it does with most El Niño events, monsoon rainfall correlates negatively with the PDO index. Insofar as circulation arising from Pacific SSTs associated with El Niño events is responsible for the enhanced precipitation, they offer strongest support for the 1997–1998 event being the most like that in pre–Ice Age time, but clearly, this is not a strong argument. (We make no attempt to correlate pre–Ice Age temperatures with El Niño teleconnections.)

China

Northern China commonly is drier than normal during both El Niño years (Fig. 12A) and periods with a positive phase of the Pacific Decadal Oscillation, at least for the past 50 yr (Fig. 12B). (A longer time series for the Pacific Decadal Oscillation suggests a somewhat different pattern in eastern China [Shen et al., 2006]). The area affected by El Niño lies largely north of the Yangtze River (but also includes a segment of it) and extends northward across the Loess Plateau and eastward into the basin in which Beijing lies. All of Allan et al. (1997), Curtis and Adler (2003), Curtis et al. (2001), Diaz and Pulwarty (1994), Lau and Sheu (1991), and Mason and Goddard (2001) reported relatively low rainfall over North China and the Loess Plateau region during El Niño summers and autumns, but the signals are not as strong as those recognized earlier for other regions by Ropelewski and Halpert (1987) in their compilation. Studies that focused specifically on China show clear correlations between low rainfall and El Niño (Nicholls, 1992; Wang and Mearns, 1987; Wang and Zhao, 1981; Whetton et al., 1990); Whetton et al. (1990) found that the correlation works best for boreal summer months, the wet season in North China. Large El Niño events seem to be particularly well correlated with drought in northern China; Nicholls (1991) noted that the big El Niño years of 1877 and 1982–1983 were associated with drought in North China, and the 1997–1998 El Niño also is associated with low rainfall (Fig. 12A).

By contrast, southern China exhibits the opposite correlation with ENSO and with the Pacific Decadal Oscillation (Fig. 12). Lau and Sheu (1991) and Dai et al. (1997) reported flooding in South China in 1982–1983 El Niño and heavier rainfall during El Niño than La Niña years. The 1997–1998 El Niño fits this pattern (Fig. 12A). Mason and Goddard (2001), however, showed that the connection is strongest in winter and resolvable only for El Niño, not the opposite correlation for La Niña. Zhang and Sumi (2002) reported much the same: relatively high rainfall over southern China during the mature phase of El Niño.

Unlike the differences between rainfall over northern (Li Chongyin, 1990) and southern China, temperatures in both the north (Li Chongyin, 1990) and south (Alexander et al., 2002) seem to be higher during El Niño years than normal times. Klein et al. (1999) suggested that during El Niño enhanced subsidence over the South China Sea reduces cloud cover, and enhanced solar radiation warms the ocean during El Niño events. We are not aware of paleoclimatic data, however, that constrain pre–Ice Age climates in southern China.

The magnetic susceptibility of loess deposited in northern China records apparent changes in climate. Relatively low deposition rates before 3–4 Ma gave way to accumulation of "red clay," aeolian deposits, followed by rapidly accumulating loess layers that alternate with

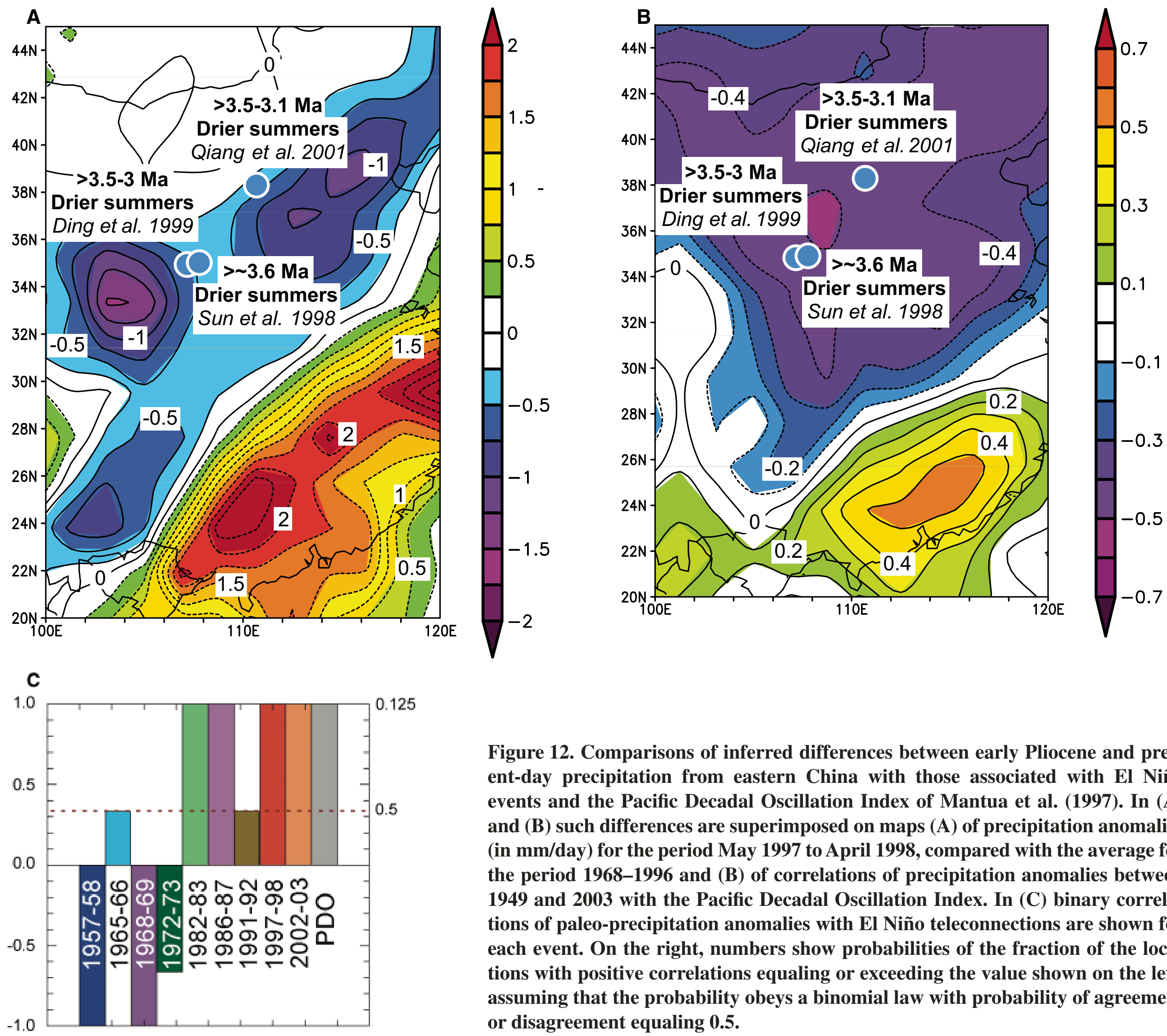


Figure 12. Comparisons of inferred differences between early Pliocene and present-day precipitation from eastern China with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B) such differences are superimposed on maps (A) of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996 and (B) of correlations of precipitation anomalies between 1949 and 2003 with the Pacific Decadal Oscillation Index. In (C) binary correlations of paleo-precipitation anomalies with El Niño teleconnections are shown for each event. On the right, numbers show probabilities of the fraction of the locations with positive correlations equaling or exceeding the value shown on the left, assuming that the probability obeys a binomial law with probability of agreement or disagreement equaling 0.5.

paleosols. Magnetic susceptibility in the "red clay" began to rise between 4.2 and 3.6 Ma, and since that time it has been larger during interglacial than glacial times (An, 2000; An Zhisheng et al., 2001; Ding et al., 1999; Qiang et al., 2001; Sun et al., 1998). Magnetic susceptibility is associated with the small grains of magnetite that form as soils form and, hence, when there is sufficient moisture (and warmth) for soil to develop. Thus, the rise in magnetic susceptibility is commonly associated with an increase in moisture, particularly in summer when precipitation is greatest. Accordingly, the increase in magnetic susceptibility records a shift from drier to more moist conditions, as we would expect, if climate shifted from El Niño–like conditions to present-day more La Niña–like conditions (Fig. 12).

Grain sizes of loess increased at ca. 2.7 Ma, which suggests that winds strengthened then (An Zhisheng et al., 2001; Xiong et al., 2003), although Qiang et al. (2001) suggested that the increase began earlier and spans the interval from 3.5 to 3.1 Ma. By analogy with modern climate, this would suggest stronger winds in the spring, when dust storms are most common.

The lowered precipitation over the Loess Plateau during El Niño events (Fig. 12) is clearest for the 1982–1983, 1986–1987, 1997–1998, and 2002–2003 events and for the Pacific Decadal Oscillation. Perhaps the common feature of the equatorial Pacific SST anomalies associated with the first three of these El Niño events and the PDO is that the highest SSTs lie farther east for them than for most El Niño events (Fig. 1).

As noted earlier in this paper, Krishna Kumar et al. (2006) showed that monsoon rainfall over India correlates with an eastward displacement of high sea-surface temperatures in the Pacific. The logic of such a correlation derives from El Niño's impact on tropical atmospheric circulation; the locus of ascent shifts eastward during El Niño, and the resulting locus of descent, which commonly lies over the western Indian Ocean, also shifts eastward during El Niño. Descent over India suppresses convection and therefore rainfall. Thus, rainfall over India is suppressed by this shift associated with El Niño, unless the shift is large enough that the anomalous descent lies east of India. When such large eastward shifts in the locus of descent occur, we might expect that it would suppress rainfall over China, as seems to have occurred in 1982–1983, 1986–1987, and 1997–1998.

Australia

Drought commonly occurs over most of Australia during El Niño (Fig. 13) (e.g., Curtis and Adler, 2003; Dai et al., 1997; Diaz et al., 2001; Kiladis and Diaz, 1989; Lau and Sheu, 1991; Mason and Goddard, 2001; McBride and Nicholls, 1983; McDonald et al., 2004; Nicholls, 1991, 1992; Ropelewski and Halpert, 1987, 1996; Suppiah, 2004; Whetton et al., 1990). Ropelewski and Halpert (1987) stated that northern and northeastern parts are dry in boreal winter, central Australia is dry throughout virtually the entire El Niño year, and southern Australia and Tasmania are dry in boreal summer. Correspondingly, flooding is commonly associated with La Niña (Kiem et al., 2003; Mason and Goddard, 2001; Nicholls, 1991; Ropelewski and Halpert, 1989).

Although drought occurred during the relatively large El Niño of 1982–1983 (Allan and Heathcote, 1987), the 1997–1998 El Niño was different (e.g., Suppiah, 2004) (Fig. 14A). Curtis et al. (2001) wrote that one difference between the 1997–1998 El Niño and others was "unusually wet conditions over northeast Australia during the later stages of the El Niño"; northeast Australia is the most sensitive part of the continent to ENSO (Fig. 13). Moreover, using a GCM with equatorial Pacific SSTs appropriate for 1997–1998, Stockdale et al. (1998) calculated only slightly drier conditions than normal in Australia. Although Kiladis and Diaz (1986) made no mention of unusual rainfall during the very large El Niño event of 1877–1878, Nicholls (1991) did note low rainfall in northeastern Australia at that time, as would be typical of the canonical El Niño teleconnection.

Precipitation over Australia correlates positively with the Pacific Decadal Oscillation index of Mantua et al. (1997), though correlations are not as large as those for temperature or precipitation in North America. When the eastern Pacific is warm, rainfall increases over most of Australia (Fig. 14B). Moreover, Power et al. (1999) showed that the reduced precipitation in Australia during El Niño events is more pronounced and better correlated when the eastern Pacific is relatively cold on decadal time scales, and conversely, when the eastern Pacific is warm, the correlation is weaker. Power et al. (1999) used an index for Pacific decadal variability that differs somewhat from that of Mantua et al. (1997), but they reported similar patterns for all indices of decadal variability.

Most paleoclimatic evidence from Australia calls for growing aridity during late Cenozoic time, with late Miocene-early Pliocene time less arid than today (Fig. 14). Archer et al. (1995) deduced from fossil plants and animals that aridification began in late Miocene time (6–8 Ma), but the shift toward a modern climate came later. They inferred that grasslands have spread since 3.4 Ma. They also reported that early Pliocene fauna in northern South Australia resembled those that live in a sclerophyll forest today, but evidence of early Pliocene mud flats and saline lakes suggest that by 3.9 Ma the environment had become more arid. They saw this as the earliest evidence of an arid climate in central Australia, and by 3.4 Ma, a yet more mesic environment seems to have developed. Consistent with this, Fujioka et al. (2005) dated the formation of a stony desert in central Australia at 2–4 Ma, approximately concurrent with the shift from pre–Ice Age to Ice Age time.

In southeastern Australia, in Victoria, both fossil plant fragments (Archer et al., 1995; Kershaw et al., 1994) and vertebrates typical of wet, forested environments (Bowler, 1976) suggest that rain forests were common in earliest Pliocene time, at 4.5 Ma. Late Pliocene fauna, however, suggest a mixture of forest and grasslands. Farther north in southeastern Queensland, fossil fauna suggest an open forest environment at 3.4 Ma; that region is quite arid today. Using fossil pollen, Martin (1994) offered estimates of annual rainfall in southeastern Australia for different periods: early-mid Miocene, >1500 mm/yr; late Miocene, 1000–1500 mm/yr; early Pliocene, 1500 mm/yr again; and late Pliocene-Quaternary, first 1000–1500 mm/yr and dropping with time to 500–800 mm/yr today. She based these on the types of forests represented by the different pollen assemblages and associated present-day rainfall. Similarly for southwestern Australia, early Pliocene fossil pollen suggest a warm, dry Mediterranean climate with low rainfall (400–800 mm/yr) (Bint, 1981). Bint (1981) also reported some *Nothofagus* and other pollen, which may have been carried from afar, but, if not, would suggest a yet more humid climate. In either case, the early Pliocene climate was less arid than today.

The general pattern of drought during El Niño (Fig. 13) and heavier than normal rain, if not flooding, during La Niña is not consistent with a shift from an El Niño–like climate to the present-day weak La Niña state, and this makes Australia appear as an exception to the global pattern that we defend in this paper. The absence of a correlation for the 1997–1998 El Niño (Fig. 14), however, raises the question: could the typical El Niño teleconnection pattern provide an inaccurate prototype for late Miocene-early Pliocene climates? Perhaps, at that time, the eastern Pacific was even warmer than it was during the 1997–1998 El Niño event. Similarly, the positive correlation of El Niño teleconnections and late Miocene-early Pliocene versus present-day differences suggests that the sea-surface temperatures in the eastern Pacific influenced global climates more than those in the central Pacific.

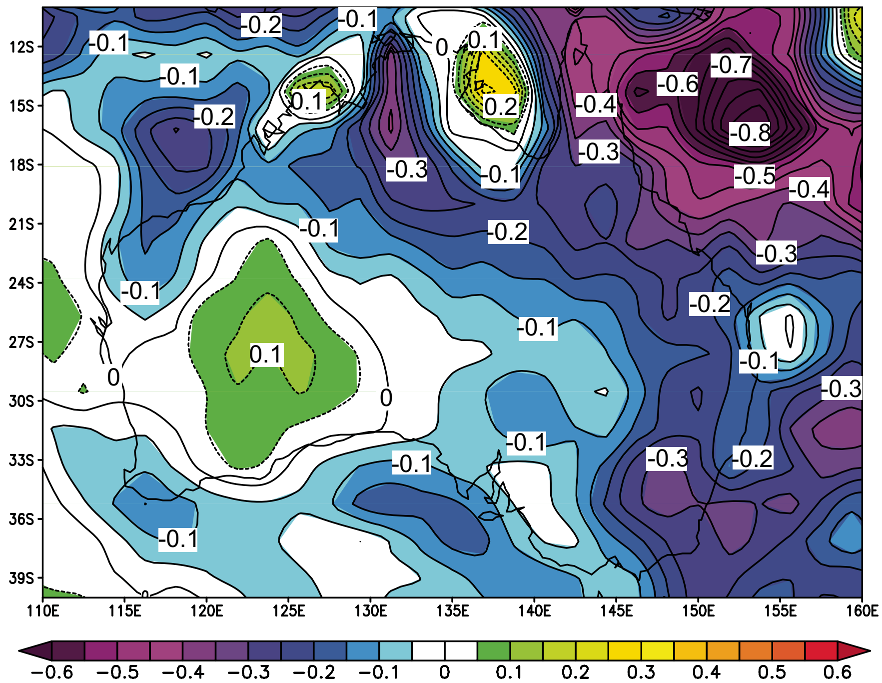


Figure 13. Map of composite annual precipitation anomalies (in mm/day) from Australia for the nine El Niño years, 1957–1958, 1965–1966, 1968–1969, 1972–1973, 1982–1983, 1986–1987, 1991–1992, 1997–1998, and 2002–2003, each covering the twelve months from May of the first year to April of the second, and referenced against the corresponding mean monthly rainfall between 1968 and 1996. Note that rainfall is lower than normal most of Australia during typical El Niño events.

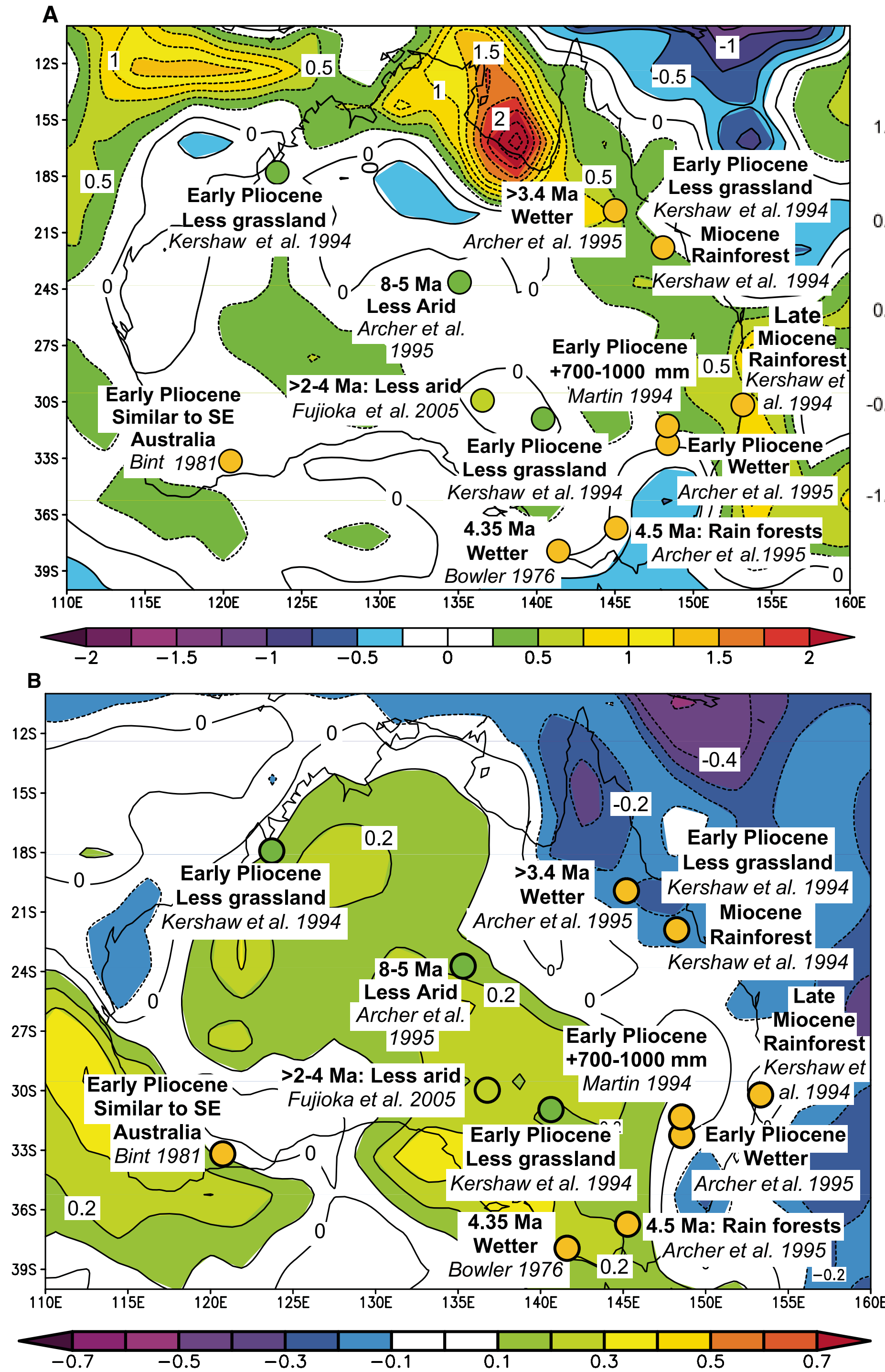
Barreiro et al. (2006) showed that with a warm tropical SST distribution their GCM runs replicate both El Niño teleconnections and corresponding differences between pre–Ice Age and present-day climates, but a major exception is that they simulated somewhat wetter, not drier, climates over Australia. (They also calculated wetter climates over most of India, but a drier one over northeast India.) The relevance of these GCM simulations is difficult to assess, in part because they assigned the present-day annual cycle of SSTs along the dateline in the central Pacific Ocean to the entire tropics between 40°S and 30°N, not just the eastern Pacific. Thus, some of their results surely are due to warmer tropics in regions outside the eastern Pacific.

SUMMARY

To a first approximation, differences between late Miocene-early Pliocene and present-day climates resemble those that we associate with El Niño. A wealth of paleoceanographic data requires a warm eastern equatorial Pacific Ocean at ca. 3–4 Ma (Chaisson and Ravelo, 2000; Lawrence et al., 2006; Ravelo et al., 2004, 2006; Wara et al., 2005), and other paleoceanographic observations suggest a shallower thermocline in the western equatorial Pacific Ocean at that time (Chaisson, 1995; Chaisson and Leckie, 1993); both are hallmarks of an El Niño state. Moreover, late Miocene-early Pliocene climates elsewhere differ from present-day climates with the same sense as El Niño teleconnections. Specifically, Alaska, Canada, and surrounding areas were warmer before ice sheets waxed and waned in this region (Fig. 2). The western United States was wetter, as it tends to be during El Niño summers (Fig. 3). By contrast, the southeastern United States and the region surrounding the Gulf of Mexico were cooler than at present, as they are during El Niño (Figs. 4 and 5). Although less convincing than for observations in North America, paleoclimatic data are consistent with a drier Amazon Basin, a wetter west coast of South America, and a warmer and wetter area near southern Brazil and eastern Argentina than at present (Fig. 6). Also consistent with a similarity of early Pliocene climates with El Niño teleconnections, the region surrounding the western Mediterranean Sea was warmer at that time than at present (Fig. 7). For different reasons, West Africa was warmer (Fig. 9) and East Africa was wetter (Fig. 10) than today, as both tend to be during El Niño years. Also, northern China seems to have been drier in early Pliocene time than today (Fig. 12), as it is during El Niño years. The prominent exceptions to this similarity of paleoclimate and El Niño teleconnections are suggestions of wetter late-Miocene-early Pliocene climates in India (Fig. 11) and Australia (Figs. 13 and 14), which seem to be opposite to the usual association of weakened monsoons and drought in these regions during El Niño events.

Even ignoring natural variability in global climate, the nature of El Niño itself makes each El Niño unique. Although all are associated with warming of the eastern equatorial Pacific Ocean, both the timing and the spatial extent of that warming differ from one El Niño to the next, and the resulting teleconnections also differ. Thus, despite the qualitative similarities of pre–Ice Age climates and El Niño teleconnections, we should not expect all to match. In particular, the 1997–1998 El Niño, the largest since instrumental recording allows a global analysis of teleconnections, was accompanied by a normal monsoon in India (Fig. 11) and slightly greater rainfall than normal over Australia (Fig. 14) rather than with the droughts typical of most El Niño events. The other El Niño event with little impact over India and Australia occurred in 1986–1987, but its impact on South America was opposite to that of nearly all other El Niños and of the canonical teleconnections (Figs. 6C, 11B, and 14C). Insofar as late-Miocene-early Pliocene climates suggest a permanent El Niño–like state, one might anticipate that resemblance to a modern El Niño event will work best for one that is both large and early, such as that of 1997–1998: large, so that it will resemble the early Pliocene equatorial Pacific in being warm very far to the east, and early, so that the impact of those warm anomalies will have already developed by boreal summer (Ihara, 2007), in time to impact the monsoon in the same manner as a permanent El Niño state.

Although the amplitude of sea-surface temperature variations associated with the Pacific Decadal Oscillation is smaller than that of even the weakest El Niño, the crude similarity of the spatial patterns allows them to be seen as variations on the general theme of a warm eastern equatorial Pacific. The longer duration of the PDO suggests that it might be the best modern analogue for pre–Ice Age sea-surface temperature distributions. Insofar as both the PDO and an El Niño event bear a strong resemblance to the early Pliocene pattern, it is tempting to infer that the part of the PDO SST distribution that characterized early Pliocene time is the part it



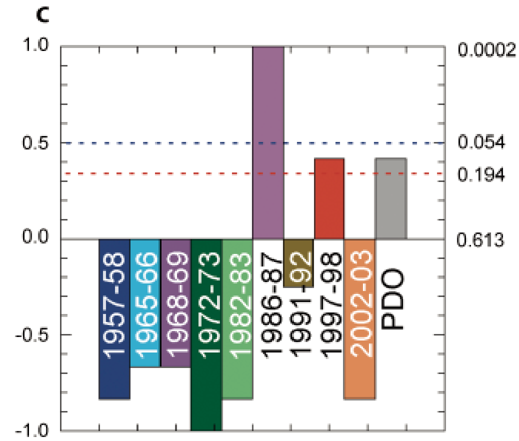


Figure 14. Comparisons of inferred differences between late Miocene-early Pliocene and present-day precipitation from Australia with those associated with El Niño events and the Pacific Decadal Oscillation Index of Mantua et al. (1997). In (A) and (B) such differences are superimposed on maps (A) of precipitation anomalies (in mm/day) for the period May 1997 to April 1998, compared with the average for the period 1968–1996 and (B) of correlations of precipitation anomalies between 1949 and 2003 with the Pacific Decadal Oscillation Index. In (C) binary correlations of paleo-precipitation anomalies with El Niño teleconnections are shown for each event. On the right, numbers show probabilities of the fraction of the locations with positive correlations equaling or exceeding the value shown on the left, assuming that the probability obeys a binomial law with probability of agreement or disagreement equaling 0.5.

has in common with El Niño, the warming of the water along the equator, not that far from the equator (Fig. 1C).

We offer a quantitative, but hardly definitive, demonstration of the inferences that, among El Niño teleconnections, those from the 1997–1998 El Niño mimic pre–Ice Age conditions best, and that the PDO mimics these conditions better than most El Niño events. Beginning with Alaska, the Canadian Arctic, and Greenland, we sum the cumulative correlations for the various regions for each El Niño event (Fig. 15). It is notable that only for 1997–1998 are correlations positive for each region, so that by the criterion of “most regions in agreement,” the 1997–1998 event comes out best. It also “wins,” if the criterion is highest summed (or average) correlation. The second highest summed (or average) correlation is for the PDO.

One could argue that we place too much emphasis on the few areas not consistent with canonical El Niño telecommunications, such as India and Australia. One might also argue that we weight equally regions with many observations, such as precipitation in the western United States or temperatures in the western Mediterranean, and regions with very few observations, like South America precipitation and West Africa temperatures. Moreover, as noted above, comparisons in each region are incomplete for a variety of reasons, such as sampling only in northern India, or clusters of measurements near one another in several regions. Finally, we chose to ignore some areas where the teleconnection patterns are complicated (e.g., precipitation around the Mediterranean) or hard to relate unambiguously to the tropical Pacific (precipitation in East Africa). Thus, although the correlation sum offers a measure of the correspondence to pre–Ice Age climate, we cannot claim that it is the ideal tool for assessing it. Nonetheless, by this or any other sensible criteria we thought of, the 1997–1998 El Niño emerges as the best match.

It would overstate our argument to assert that every departure of the pre–Ice Age climate from modern conditions can be explained as a response to equatorial Pacific SST patterns. Perhaps the clearest signal of change since pre–Ice Age time is that of Marlow et al. (2000) for sea-surface temperatures off the west coast of Southwest Africa. Correlations with any El Niño, the 1997–1998 El Niño, or the Pacific Decadal Oscillation are weak at best. Understanding the climate links connected to this feature would be a further step in understanding pre–Ice Age climate. Perhaps they have nothing to do with what is now dubbed the permanent El Niño in the equatorial Pacific, or perhaps there is a reason why the teleconnection pattern out of the Pacific was different ca. 3–5 Ma ago.

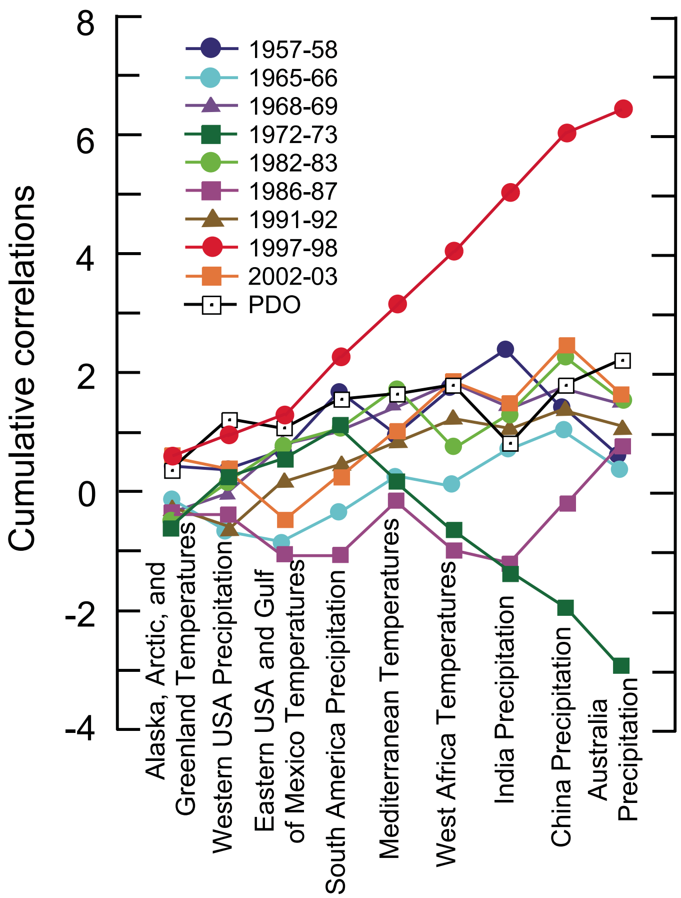


Figure 15. Cumulative sums of correlations over the different regions (shown in Figures 2C, 3C, 5D, 6C, 7C, 9B, 11B, 12C, and 14C) for each El Niño event. Note that correlations are positive for each region for the 1997–1998 El Niño, and as a result the cumulative sum is by far the largest. The second highest cumulative sum is for the Pacific Decadal Oscillation (PDO).

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