Evidence for El Niño–like conditions during the Pliocene

***Ana Christina Ravelo, Petra Simonne Dekens, Matthew McCarthy**, Ocean Sciences Department, University of California, Santa Cruz, California 95064, USA*

ABSTRACT

The modern tropical Pacific Ocean is characterized by strong east-west asymmetry in sea surface temperature and subsurface thermocline depth coupled to easterly trade winds and zonal atmospheric, or Walker, circulation. Walker circulation and the "normal" east-west asymmetry of sea surface temperature and thermocline depth break down temporarily during El Niño events. Since these temporary deviations from the "normal" tropical climate state are known to have global impacts, it is important to consider whether permanent shifts in the mean tropical Pacific climate state are an integral part of global climate change on longer time scales. To understand the link between tropical conditions and global warmth, we focus our study on the early Pliocene, the most recent period in Earth's history of sustained global warmth relative to today. A data synthesis of tropical paleoceanographic data, including a new alkenone unsaturation index ($U_{37}^{k'}$)–based sea surface temperature record from the eastern equatorial Pacific, indicates that, in the early Pliocene, the east-west asymmetry in sea surface temperature and thermocline depth was reduced compared to today and the tropical Pacific was in a permanent El Niño–like state. Thus, the "normal" mean state of the modern tropical Pacific is not a persistent feature of Earth's climate over long time scales.

INTRODUCTION

Studies of the El Niño Southern Oscillation (ENSO) phenomenon indicate that, through atmospheric teleconnections, small changes in the pattern of tropical Pacific sea surface temperature (SST) have a global impact on interannual time scales (Alexander et al., 2002). Although the mechanisms responsible for the ENSO do not directly apply to studies of climate changes on longer time scales, ENSO events provide a clear example of how changes in the distribution of SST across the Pacific Ocean can have far-field climate effects such as higher than average rainfall in the southwestern United States and higher than average temperature in temperate regions of North America. The potential global effect of small, long-term changes in the tropical SST pattern is substantiated by modeling studies (Yin and Battisti, 2001; Barreiro et al., 2005). However, while the impact of changes in the mean SST pattern of the tropical Pacific on global climate is recognized, the circumstances under which they could occur are difficult to predict. For example, in simulations of future climate change forced with enhanced greenhouse gases, climate models do not give consistent results in the tropical Pacific: some predict no long-term changes; some predict El Niño–like mean conditions; still others predict La Niña–like mean conditions (Cane, 2005; Collins, 2005). Because the instrumental record is too short to examine multidecadal and longer-term climate changes, paleoceanographic studies are needed to establish whether modern mean tropical SST patterns across tropical basins are stable over long time periods. These data-based studies can then be used to test and improve theoretical and computer models of long-term climate change, including those that are used to predict future climate change.

While much can be learned from studying the extreme globally cool climate of the Last Glacial Maximum (LGM), it is also important to focus on past periods of global warmth prior to the ice ages of the past few million years. Paleoceanographic studies generally indicate that the mean SST of the Pacific tropical ocean was stable within a few degrees over millions of years, yet these studies rarely include enough data to characterize the east-west SST difference across the Pacific. For example, the Pliocene warm period (ca. 4.5–3.0 Ma) (Fig. 1) has been the focus of much interest among paleoclimatologists because of the need to understand climate processes in past times of global warmth. Landmark studies, such as those by the Pliocene Research, Interpretation, and Synoptic Mapping (PRISM) group, including compilations of oceanic and terrestrial data (Dowsett et al., 1996, 2005; Thompson and Fleming, 1996) and modeling studies (Haywood et al., 2000; Sloan et al., 1996), indicate that the Pliocene was significantly warmer than today, especially in extratropical regions. However, the PRISM reconstructions include very little data from the tropical Pacific Ocean and therefore do not provide insight into changes in tropical SST patterns. Crowley (1996) pointed out the urgent need for more tropical data in order to further constrain the mechanisms that explain global climate conditions in the Pliocene, and in the last decade, several studies were conducted that focus on the tropical Pacific utilizing Pliocene-age material obtained by the Ocean Drilling Program.

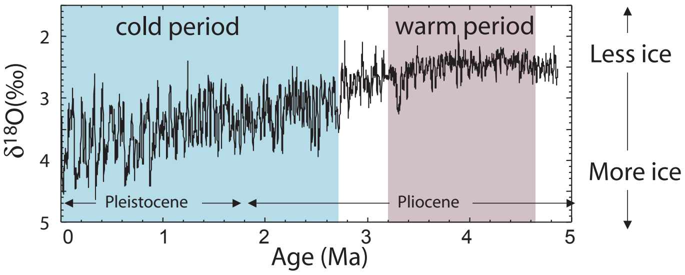

Figure 1. Benthic foraminifera $\delta^{18}O$ record of high-latitude climate (primarily ice volume) from Ocean Drilling Program (ODP) Site 677 (Shackleton et al., 1990) and ODP Site 1085 (Andreasen, 2001). The end of the Pliocene warm period and the onset of Northern Hemisphere glaciation occurred ca. 3.0 Ma.

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The purpose of our study is to present a comprehensive view of tropical Pacific conditions during the Pliocene warm period that takes into account the most recent results in order to assess the importance of tropical conditions in determining Pliocene warmth. Overall, recent results indicate that in the Pliocene warm period the pattern of SST across the Pacific was quite different and resembled a permanent El Niño–like mean state (Wara et al., 2005). Because of the need for multi-proxy studies, we have generated a new SST record, based on alkenone-paleothermometry, to confirm the Mg/Ca-based estimates of warmer than modern SSTs in the eastern equatorial Pacific. In addition, a compilation of paleoceanographic reconstructions of the subsurface (~100 m below sea level) shows that the permanent El Niño–like state was coupled to a deeper or warmer thermocline in the east equatorial Pacific, indicating that thermocline conditions may play an important role in determining the long-term mean state of the tropical Pacific.

EAST-WEST ASYMMETRY OF THE MODERN TROPICAL PACIFIC OCEAN

During "normal" conditions in the modern tropical Pacific Ocean, easterly trade winds drive the flow of equatorial currents from the east to the west, resulting in a thick, warm, mixed layer in the western equatorial Pacific underlain by a deep (~200–400 m) thermocline, the steep thermal gradient between the warm, mixed layer above and the cooler water below (Fig. 2). In the eastern equatorial Pacific, the thermocline is relatively shallow (~50 m). The easterly trade winds drive divergent upwelling along the equator, causing SST to be relatively cool only in the eastern equatorial Pacific where the thermocline is shallow; in the western equatorial Pacific, SSTs remain warm because cool subsurface waters within and beneath the thermocline are deep. Thus, as a result of the easterly trade winds and a shallow thermocline in the east relative to the west, there is a strong east-west SST difference across the equatorial Pacific (~5 °C during normal conditions). Sinking air and dry conditions over the eastern equatorial Pacific due to cooler SST and rising air and relatively high precipitation rates over the western equatorial Pacific due to warmer SST result in a sea level pressure (SLP) gradient that enhances the easterly trade winds, which further augments the east-west SST contrast, SLP and precipitation gradients, winds, and so on. The atmospheric circulation cell, comprised of easterly trade winds, rising air in the western equatorial Pacific, westerly flow

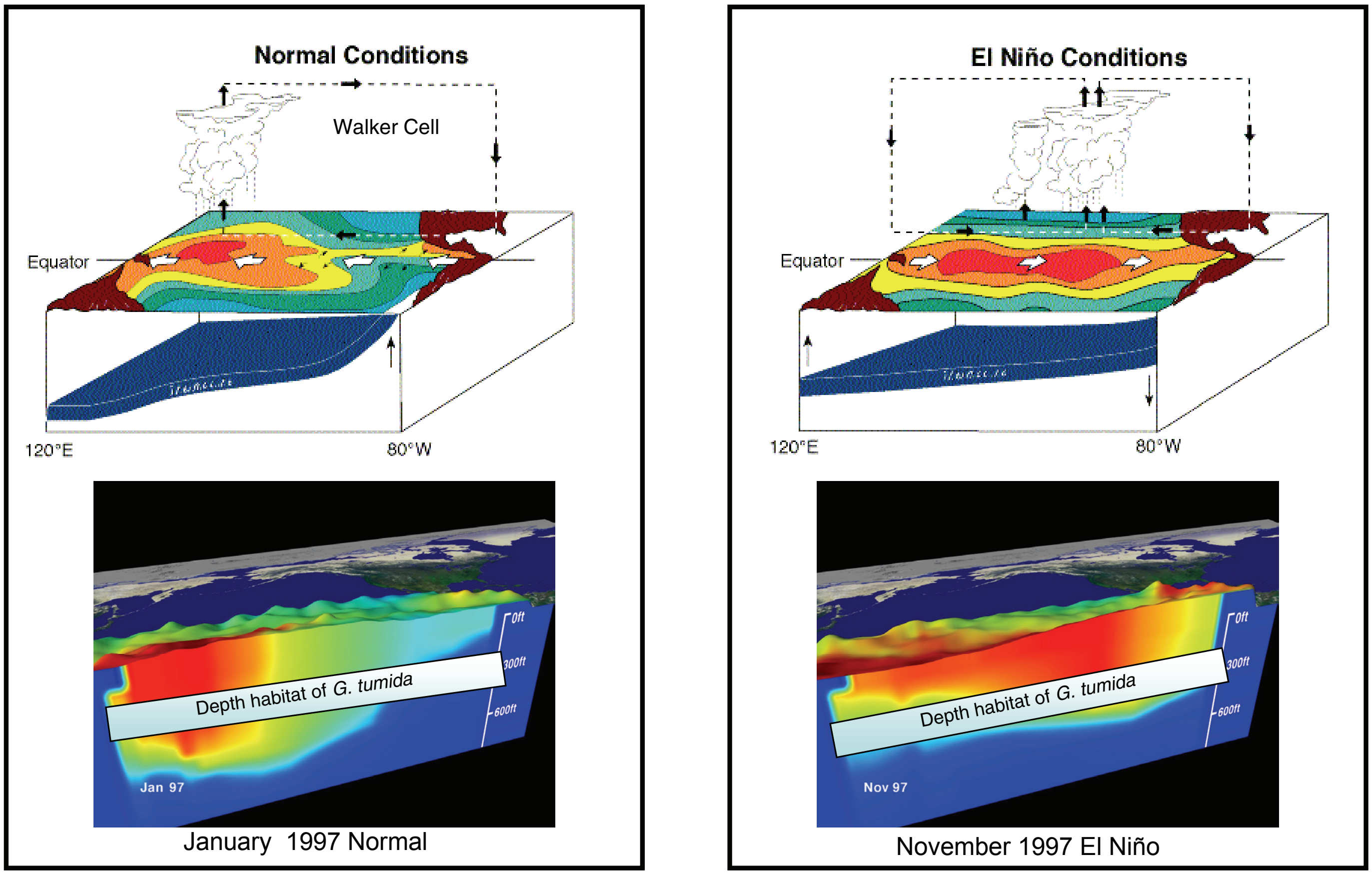

Figure 2. Comparison of normal and El Niño conditions in the modern ocean (adapted from the National Oceanic and Atmospheric Administration [2005] El Niño Web site, www.pmel.noaa.gov/tao/elnino). Schematic of normal conditions includes strong Walker circulation or convective loop and strong east-west temperature gradient and thermocline tilt (upper left); schematic of El Niño conditions includes weakened Walker circulation, temperature gradient, and thermocline tilt (upper right). Lower left: equatorial Pacific cross sections of temperature prior to El Niño (January 1997), when subsurface temperature gradient is relatively large; lower right: during an El Niño (November 1997), when subsurface temperature gradient is relatively small. Sea surface height is represented by bumps. Temperature range is from 30 °C (red) to 8 °C (blue). The thermocline is approximately at the 20 °C isotherm (the border between dark blue and cyan). The depth habitat of *G. tumida*, the species used to monitor subsurface temperature, is indicated.

aloft, and sinking air over the high SLP region in the eastern equatorial Pacific, is called Walker circulation (Fig. 2). Air-sea feedbacks maintain a strong Walker circulation and the asymmetric pattern of conditions across the equatorial Pacific, which is the stable mean state of the tropical Pacific today.

An El Niño event, which occurs every few years, includes the temporary breakdown of Walker circulation accompanied by a more symmetrical pattern of SST, SLP, and thermocline depth across the Pacific (Fig. 2). In addition, rainfall patterns change with relatively dry conditions (drought) in the western equatorial Pacific and high rates of precipitation in the eastern equatorial Pacific. ENSO events are considered to be extreme swings, or interannual variability, superimposed on the stable mean zonally asymmetric state described above. Much less is known about decadal and longer time scale oscillations and trends. Although tropical climate signals may also have decadal variability (Liu and Huang, 2000; Philander and Fedorov, 2003a), the instrumental record is too short to allow differentiation between decadal variability and long-term shifts. Thus, it is not clear whether changes in the mean state are related to the global warming of the last century.

Both decadal-scale variability and longer-term changes in the mean tropical climate could be related to changes in the subsurface thermocline, which could influence SST in upwelling regions. For example, when the thermocline is relatively deep, the SST in the eastern equatorial Pacific would be relatively warm, and vice versa. Factors that might influence the thermocline over long time scales are the latitudinal temperature gradient (Boccaletti et al., 2004), the latitudinal salinity gradient (Fedorov et al., 2004), and mid-latitude winds in the region where water is subducted into the thermocline (Liu and Yang, 2003; Sun et al., 2004). Displacement of the thermocline over long time scales could cause changes in SST in upwelling regions, such as the eastern equatorial Pacific, thereby altering the mean tropical Pacific climate state. Whether or not this could happen in the future is unknown; there may or may not be feedbacks that, regardless of the forcing or perturbation, keep Walker circulation strong and stable on average and prevent tropical conditions from deviating from its current asymmetric pattern. Geologic studies of past warm periods that monitor changes in the west-east asymmetry of SST and thermocline depth, and by inference the strength of Walker circulation, can be used to assess the long-term stability of tropical Pacific climate and the factors that might be responsible for long-term changes in mean conditions if they occurred.

EVIDENCE FOR REDUCED EAST-WEST ASYMMETRY DURING THE PLIOCENE

Foraminifera Assemblages

Sediment cores recovered during Ocean Drilling Program (ODP) Leg 130 in the western equatorial Pacific and Leg 138 in the eastern equatorial Pacific have been used to characterize open ocean conditions across the Pacific in a number of different studies published over the past ten years or so. The first study (Chaisson, 1995) to focus on development of east-west gradients across the Pacific during the Pliocene and Pleistocene utilized planktonic foraminifera assemblages in the western equatorial Pacific (ODP site 806) and eastern equatorial Pacific (ODP site 847) (Fig. 3). In the tropics, planktonic foraminifera mainly grow in the upper 100–150 m of the water column and are depth stratified. Census counts of an assemblage can be used to determine changes in surface and subsurface conditions. In the modern ocean, there is a strong asymmetry in the planktonic foraminifera assemblages across the Pacific, with species that thrive in the mixed layer dominating the western equatorial Pacific, where the mixed layer is thick and occupies the entire photic zone (upper 100–150 m). In the eastern equatorial Pacific, where cool nutrient-rich water upwells into the photic zone and stimulates biological productivity, the assemblages are more diverse and include mixed-layer species as well as those indicative of higher levels of productivity (Andreasen and Ravelo, 1997).

Chaisson (1995) showed that planktonic foraminifera assemblages in the western equatorial Pacific were more similar to those in the eastern equatorial Pacific during the early Pliocene relative to today, indicating that the east-west asymmetry of upper ocean conditions in the early Pliocene was reduced compared to today. The abundances of foraminifera species indicative of productivity increased throughout the Pacific just after 4.0 Ma, but the strong east-west difference in assemblages found today developed after ca. 3.0 Ma and intensified at the beginning of the Pleistocene epoch (ca. 1.6 Ma). These results indicate that in the Pliocene warm period, there were weak easterly trade winds on the equator (much like during an El Niño) and that modern-like east-west asymmetry in SST and thermocline depth must have developed as global climate cooled (Chaisson, 1995). Because many of the species Chaisson (1995) used are now extinct, he had to make a number of assumptions about paleoecology and depth habitat and his results are not quantitative. To better quantify changes in

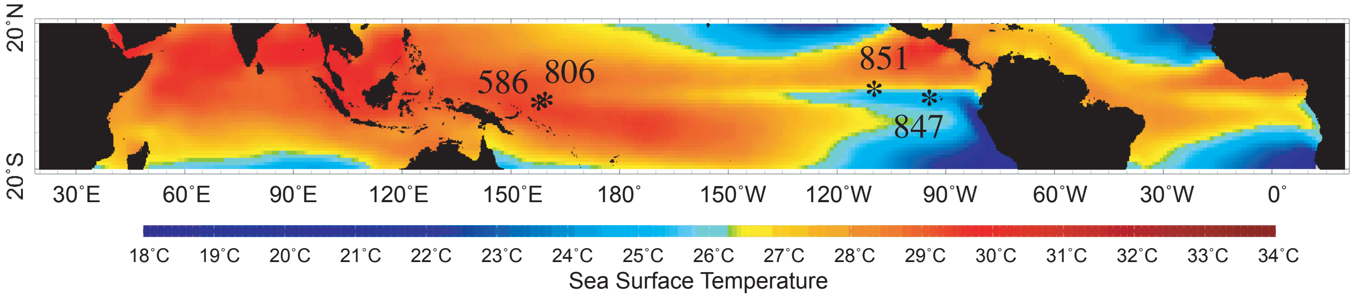

Figure 3. Sea surface temperature (SST) map (October climatology) of the tropical Pacific (Reynolds and Smith, 1994). Change in the strong SST gradient across the equatorial Pacific is monitored in this paper by using Deep Sea Drilling Project Site 586 (0.50°S, 159°E, 2507 m), Ocean Drilling Program (ODP) Site 806 (0°N, 159°E, 2520 m), ODP Site 847 (0°N, 95° W, 3373 m), and ODP Site 851 (3°N, 111°W, 3761 m).

the east-west surface and subsurface temperature differences across the tropical Pacific through the Pliocene, the application of geochemical measurements is required.

Geochemical Sea Surface Temperature Estimates

Geochemical measurements of planktonic foraminifera shells can be used to constrain changes in surface ocean conditions across the tropical Pacific. One of the most common tracers of climate change is oxygen isotope measurement ($\delta^{18}O$) of foraminifera shells. Because $H_2{}^{16}O$ evaporates more readily than $H_2{}^{18}O$, the $\delta^{18}O$ values of water vapor, cloud droplets, precipitation, and continental ice are low compared to that of seawater. Thus, the $\delta^{18}O$ of seawater is influenced by changes in local salinity, which reflects hydrological processes (evaporation minus precipitation) and changes in ice volume. The offset between the $\delta^{18}O$ composition of foraminiferal calcite ($CaCO_3$) and the $\delta^{18}O$ of seawater in which they calcify is temperature dependent. Thus, foraminiferal $\delta^{18}O$ values reflect multiple environmental parameters. Since the exact history of ice volume over the past 5 m.y. is not well known, it is most useful to look at differences between $\delta^{18}O$ records, which are not influenced by the shared variance related to ice volume fluctuations. The difference between two $\delta^{18}O$ records therefore reflects local changes (in salinity and temperature) at one location relative to another.

$\delta^{18}O$ measurements of *G. sacculifer* (without the sac-like final chamber), a species that calcifies in the surface mixed layer, from ODP sites 851 and 847 in the eastern equatorial Pacific and ODP site 806 and Deep Sea Drilling Project (DSDP) site 586 in the western equatorial Pacific, indicate that the east-west differences in local conditions (salinity and temperature) were smallest in the early Pliocene and increased ca. 1.7 Ma (Fig. 4A). The scatter of data around the smoothed curve mainly reflects glacial to interglacial changes, but there is a clear increase in the long-term average $\delta^{18}O$ difference between the eastern equatorial Pacific and the western equatorial Pacific. If this data were interpreted solely as reflecting changes in surface temperature, they would indicate the absence of an east-west SST difference across the Pacific and therefore an absence of Walker circulation in the early Pliocene. After ca. 1.7 Ma, the $\delta^{18}O$ data indicate that the SST difference increased to ~5 °C, much like the modern ocean. However, changes in precipitation or evaporation could also have occurred, thereby influencing the $\delta^{18}O$ records at either or both sites. As such, it is important to apply additional proxies that more directly reflect past ocean temperature.

Two recent studies (Rickaby and Halloran, 2005; Wara et al., 2005) include analyses of magnesium to calcium ratios (Mg/Ca) measured in planktonic foraminifera shells at two sites, ODP site 806 in the western equatorial Pacific and ODP site 847 in the eastern equatorial Pacific. The incorporation of Mg relative to Ca into foraminiferal calcite shells varies exponentially with calcification temperature (Anand et al., 2003; Dekens et al., 2002; Nürnberg et al., 1996). Records of Mg/Ca measured on shells of *G. sacculifer* (without the sac-like final chamber) from the western equatorial Pacific and the eastern equatorial Pacific can be used to quantitatively reconstruct the east-west SST difference by applying a Mg/Ca-temperature calibration (Dekens et al., 2002) (Fig. 4B and 4C). The results indicate that the eastern equatorial Pacific was ~2.5 °C warmer and the western equatorial Pacific was ~2 °C cooler in the warm Pliocene compared to today. The east-west SST difference was only ~1.5 °C in the warm Pliocene and increased to ~5 °C after ca. 1.7 Ma (Wara et al., 2005) (Fig. 4D). Concordance of the Mg/Ca measurements of *G. sacculifer* with that of *G. ruber* (Medina-Elizalde and Lea, 2005) at the western equatorial Pacific site indicate that results are not dependent on the choice of surface-dwelling planktonic foraminiferal species. A few outlier data points in the eastern equatorial Pacific (ODP site 847) from the Rickaby and Halloran (2005) study are offset from the data from the same site and time period generated by Wara et al. (2005). These outliers cannot be explained by systematic differences between the two laboratories since all other data from the two studies agree. Both groups used the same procedure to clean foraminifera shells, and the Wara et

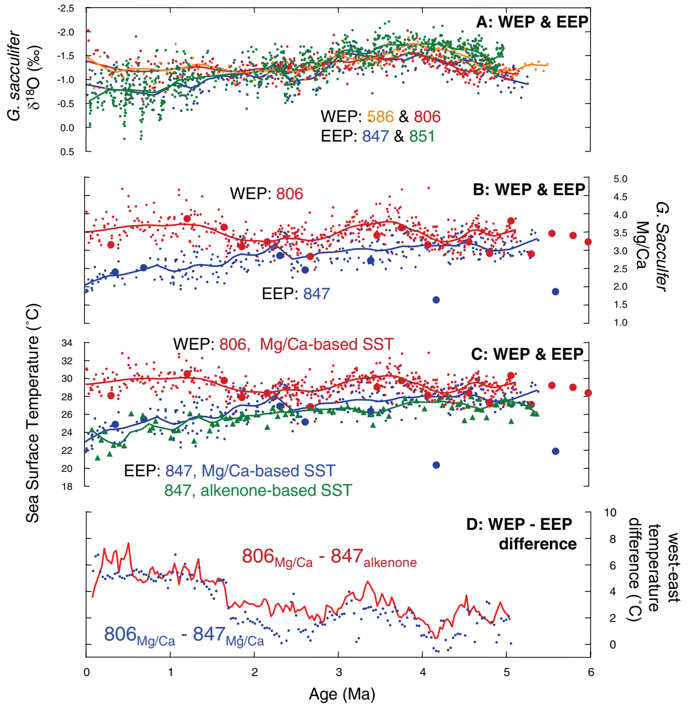

Figure 4. (A) Planktonic (*G. sacculifer* without sac-like final chamber) foraminifera $\delta^{18}O$ records from two western equatorial Pacific (WEP) locations: Deep Sea Drilling Project site 586 (orange) (Whitman and Berger, 1992) and Ocean Drilling Project (ODP) site 806 (red) (Chaisson and Ravelo, 2000; Wara et al., 2005) and two eastern equatorial Pacific (EEP) locations: ODP site 847 (blue) (Chaisson and Ravelo, 2000; Wara et al., 2005) and ODP site 851 (Cannariato and Ravelo, 1997). (B) Planktonic (*G. sacculifer* without sac-like final chamber) foraminifera Mg/Ca records from the western equatorial Pacific location, ODP site 806 (red), and eastern equatorial Pacific location, ODP site 847 (blue). Small dots and smoothed line are data from Wara et al. (2005); large dots are data from Rickaby and Halloran (2005). (C) Sea surface temperature (SST) (°C) estimates for the western equatorial Pacific site 806 (red) and eastern equatorial Pacific site 847 (blue) based on Mg/Ca records (shown in B) using Dekens et al. (2002) calibration and for the eastern equatorial Pacific site 847 (green) based on $U^{k'}_{37}$ measurements (this study). (D) The west minus east SST difference record calculated by subtracting the site 847 Mg/Ca-based SST record from the site 806 Mg/Ca-based SST record (blue) (adapted from Wara et al., 2005) and by subtracting the site 847 alkenone-based SST record from the site 806 Mg/Ca-based SST record (red).

al. group participated in an international lab comparison and calibration (Rosenthal, 2004) and found that their data were close to the median of all labs. In sum, of several hundred Mg/Ca measurements used to characterize the east-west SST difference across the tropical Pacific, there are only a few outliers, and only one in the Pliocene. Thus, we conclude that there is strong evidence, based on Mg/Ca data, for a reduced east-west SST difference indicative of weak zonal asymmetry and Walker circulation during the warm Pliocene compared to today.

Another proxy that has been used extensively in paleoceanographic studies is the alkenone unsaturation index ($U^{k'}_{37}$), which has a strong correlation with ocean temperatures in the modern ocean and has been extensively calibrated (Herbert, 2001). The $U^{k'}_{37}$ index utilizes long-chain (C_{37}) ketones synthesized by certain species of phytoplankton (coccolithophorid algae) and found in the organic fraction of the sediment. It is thus an indicator of past SST that is completely independent from the Mg/Ca proxy, which is measured on calcite shells. Our new analyses of $U^{k'}_{37}$ in sediments from the eastern equatorial Pacific (ODP site 847) (following the protocol described in Herbert et al., 1998) indicate that the eastern equatorial Pacific was warmer in the early Pliocene compared to today, corroborating SST reconstructions based on Mg/Ca data from the same site (Fig. 4C). The absolute temperatures of the $U^{k'}_{37}$ and Mg/Ca based temperature records at the eastern equatorial Pacific site depend on the calibrations used. In our study, we use commonly accepted calibrations for these environments and species: Dekens et al. (2002) for converting Mg/Ca to SST and Müller et al. (1998) for converting $U^{k'}_{37}$ to SST. Our chosen calibrations result in reasonable absolute temperatures when applied to Holocene sediments from these locations. Most notably, the magnitude of the cooling with time, which is not dependent on the chosen calibration, is similar, with both proxies predicting that the eastern equatorial Pacific was on average ~4 °C warmer in the warm Pliocene (from ca. 5 to 2.5 Ma) compared to the Pleistocene (from 1.6 to 0 Ma) and ~2.5 °C warmer compared to today. The $U^{k'}_{37}$-based SST reconstruction is further evidence that the single early Pliocene Mg/Ca data point at ca. 4.2 Ma (Fig. 4B and 4C) generated by Rickaby and Halloran (2005) does not represent the average SST conditions in the eastern equatorial Pacific during that time.

In the warm Pliocene, it was cooler in the western equatorial Pacific while it was warmer in the eastern equatorial Pacific, so that the average tropical Pacific temperature may have been a bit warmer. The few existing planktonic foraminifera assemblage–based SST estimates from the tropical Pacific (Dowsett et al., 2005) indicate that tropical temperatures were not warmer than today, but these estimates do not resolve spatial patterns across the Pacific and do not include data from the eastern equatorial Pacific. Overall, while more data are needed to quantify the average tropical Pacific temperature, there is clear evidence that east-west asymmetry in SST, and by inference Walker circulation, was reduced during the Pliocene warm period compared to today.

Geochemical Thermocline Depth Estimates

As described, analyses of Mg/Ca in *G. sacculifer* (without the sac-like final chamber) and of $U^{k'}_{37}$ in the organic fraction of the sediments support Chaisson's (1995) idea that the modern east-west asymmetry of the tropical Pacific developed through the Pliocene and into the Pleistocene. Chaisson (1995) further argued that changes in foraminiferal abundances reflect changes in subsurface conditions and the depth of the thermocline, and that the modern tilt of the thermocline, from shallow in the east to deep in the west, developed through the Pliocene and Pleistocene. Establishing linkages between the evolution of the thermocline and changes in SST are critical for understanding the processes and conditions responsible for El Niño–like conditions in the warm Pliocene.

Geochemical evidence for changes in thermocline conditions through the Pliocene and Pleistocene consists of $\delta^{18}O$ (and limited Mg/Ca) measurements of shells of species of planktonic foraminifera that live and calcify in the subsurface. In the western equatorial Pacific, a compilation of $\delta^{18}O$ data from a number of studies (Billups et al., 1999; Chaisson and

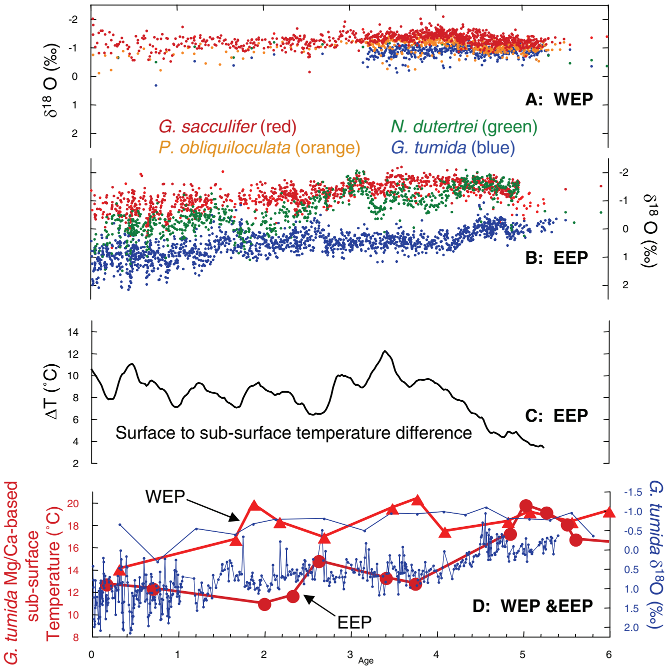

Figure 5. (A) Oxygen isotopic records of multiple species of planktonic foraminifera at western equatorial Pacific (WEP) Deep Sea Drilling Project site 586 and Ocean Drilling Project (ODP) site 806 (data from Whitman and Berger, 1995; Chaisson and Ravelo, 2000; Billups et al., 1998; Wara et al., 2005). (B) Oxygen isotopic records of multiple species of planktonic foraminifera at eastern equatorial Pacific (EEP) ODP site 847 and 851 (data from Chaisson and Ravelo, 2000; Cannariato and Ravelo, 1997; Wara et al., 2005). (C) Difference (Δ °C) between the calcification temperatures of *G. sacculifer* (without sac) and *G. tumida* at eastern equatorial Pacific ODP site 847 calculated by assuming that the difference between their $\delta^{18}O$ entirely reflects temperature and that $\Delta\delta^{18}O/0.21 = \Delta$ °C. Calculated by subtracting 0.2 Ma Gaussian (~35 data points per window) smoothed curves derived from *G. sacculifer* and *G. tumida* data in (B). (D) Comparison of subsurface conditions between western equatorial Pacific ODP site 806 and eastern equatorial Pacific ODP site 847. Oxygen isotope measurements of *G. tumida* (blue) from sites 806 (Chaisson and Ravelo, 2000) and 847 (Wara et al., 2005) and subsurface temperature estimates (red) are based on the Mg/Ca of *G. tumida* from 806 and 847 (Rickaby and Halloran, 2005). Both the $\delta^{18}O$ and the Mg/Ca-based temperature records indicate cooling of the subsurface water (especially in the eastern equatorial Pacific) through the Pliocene as the thermocline shoaled.

Ravelo, 2000; Wara et al., 2005; Whitman and Berger, 1992) indicates that the range of $\delta^{18}O$ among surface and subsurface dwelling foraminifera was always relatively small (no more than ~2‰) over the past 6 m.y. (Fig. 5A). A small $\delta^{18}O$ range among species that grow at different depths suggests that the assemblage was calcifying over a relatively small temperature and salinity range; this would be expected when cool water in and beneath the thermocline was below the photic zone where foraminifera proliferate. The $\delta^{18}O$ data therefore indicate that the mixed layer and thermocline were deep in the western equatorial Pacific throughout the Pliocene and Pleistocene. It is not possible to precisely quantify thermocline depths below the photic zone since the foraminifera species analyzed live mainly in the photic zone, and the $\delta^{18}O$ composition of their shells would not have been sensitive to fluctuations in thermocline depth below the photic zone.

The $\delta^{18}O$ measurements of multiple species in the eastern equatorial Pacific (Cannariato and Ravelo, 1997; Chaisson and Ravelo, 2000; Wara et al., 2005) indicate that there have been changes in thermocline conditions over the past 6 m.y. Specifically, the range of $\delta^{18}O$ among species was less during the interval from ca. 6 to 4.3 Ma compared to the time interval from 4.3 to 0 Ma (Fig. 5B). This indicates that the thermocline was deeper (or warmer) until ca. 4.3 Ma, after which time it shoaled or cooled, thereby bathing the deep-dwelling foraminifera in cooler water. A close look at the *N. dutertrei* record indicates that there may have been a number of changes to the thermocline structure throughout the Pliocene. But the interpretation of the *N. dutertrei* record is confounded by its erratic depth ecology and the fact that the data older than ca. 3.0 Ma are from measurements of its ancestor, *N. humerosa* (Cannariato and Ravelo, 1997), a species whose test is generally smaller in size and whose depth ecology may have been different from that of *N. dutertrei*. More straightforward reconstructions of thermocline depth can be made using *G. tumida*, a species that seems to consistently grow near the bottom of the photic zone (~100 m) (Ravelo and Fairbanks, 1992). *G. tumida* $\delta^{18}O$ values relative to those of the surface dwelling species, *G. sacculifer* (without the sac-like final chamber), reflect the difference in calcification temperature between the two species and indicate that subsurface water at ~100 m was ~5 °C warmer in the earliest Pliocene relative to today, reflecting a deeper thermocline (Fig. 5C).

Mg/Ca measurements of *G. tumida* provide a more quantitative estimate of subsurface temperature changes and agree with the interpretations based on $\delta^{18}O$ of multiple species. Mg/Ca data were used to generate low-resolution subsurface temperature records from the western equatorial Pacific (ODP site 806) and eastern equatorial Pacific (ODP site 847) (Rickaby and Halloran, 2005) (Fig. 5D). Their data indicate that while early Pliocene subsurface temperatures in the western equatorial Pacific were similar to today, they were 4–5 °C warmer than today in the eastern equatorial Pacific (Fig. 5D), in agreement with the $\delta^{18}O$ of *G. tumida* data. The warm subsurface temperatures in the eastern equatorial Pacific during the early Pliocene resemble conditions in the western equatorial Pacific today where the thermocline is relatively deep. The interpretation of Rickaby and Halloran (2005), that the warm early Pliocene subsurface temperatures in the eastern equatorial Pacific are an indication of a relatively shallow thermocline, is not supported given the depth ecology of *G. tumida* (Niebler et al., 1999; Ravelo and Fairbanks, 1992). Instead, warm calcification temperatures of *G. tumida* indicate that the cool thermocline was deep, below the depth habitat of *G. tumida*. Furthermore, the Mg/Ca data indicate that, during the earliest Pliocene, the subsurface temperature in the eastern equatorial Pacific was so warm that it was similar to that in the western equatorial Pacific (close to 17 or 18 °C), much like it is during an El Niño event (Fig. 2), again attesting to the symmetry of conditions across the equatorial Pacific during the early Pliocene warm period.

The east-west subsurface temperature difference (and therefore thermocline depth), as indicated by the Mg/Ca and $\delta^{18}O$ data of *G. tumida* (Fig. 5D), and east-west surface temperature difference, as indicated by the Mg/Ca and $\delta^{18}O$ data of *G. sacculifer* (Fig. 4), increased through the Pliocene as global climate cooled. As would be expected, development of surface and subsurface east-west asymmetry go hand-in-hand because as the thermocline shoaled in the eastern equatorial Pacific, it influenced SST through upwelling. Walker circulation, sustained by air-sea feedbacks that depend on the east-west difference in SST, must have also increased through the Pliocene.

SUMMARY AND IMPLICATIONS

Compilation of data from across the tropical Pacific indicates that surface and thermocline conditions were similar on both sides of the basin, resembling a permanent El Niño, during the warm Pliocene, and that the modern-day east-west asymmetry of the equatorial Pacific developed through the Pliocene as climate cooled. What are the global implications of this transition in tropical Pacific conditions over the past 5 m.y.? The transition is thought to have a global impact on terrestrial climate because data-based reconstructions of continental climate anomalies during the early Pliocene compared to today have an El Niño–like fingerprint (Molnar and Cane, 2002); however, the nature of teleconnections between tropical and extratropical regions that operate over long time scales will need further investigation. Observational data support the idea that the depth of the thermocline determines the strength of air-sea interactions that sustain Walker circulation with far-field global effects (Philander and Fedorov, 2003b). More specifically, shoaling of the thermocline in the eastern equatorial Pacific occurred as the amplitude of glacial-interglacial cycles increased; it appears that as the thermocline shoaled, air-sea coupling increased, and the feedbacks that amplify solar forcing of glacial-interglacial cycles were strengthened (Ravelo et al., 2004). Studies that show further strengthening of the east-west SST difference across the Pacific at the mid-Pleistocene transition (de Garidel-Thoron et al., 2005; McClymont and Rosell-Melé, 2005; Medina-Elizalde and Lea, 2005) also attest to the possible role of tropical Pacific air-sea interactions in the amplification of climate variability.

The theoretical link between strong Walker circulation and global climate conditions has been explored in modeling studies that speculate that northern hemisphere cooling and glaciation could be intimately tied to changes in the tropical Pacific mean state. These studies indicate that tropical-extratropical climate is linked in both directions. Low latitude regions are influenced by high latitude Pliocene boundary conditions through atmospheric (Haywood and Valdes, 2004) and oceanic (Philander and Fedorov, 2003b) processes. In addition, permanent El Niño–like conditions can induce global warming through changes in global albedo (e.g., due to fewer low level stratus clouds in the eastern equatorial Pacific) (Barreiro et al., 2005). While there is growing evidence that permanent El Niño–like conditions are an important feature of the Pliocene global climate, there is still no widely accepted theory for how and why the tropical changes occurred in the first place. Comparisons of paleoclimatic records from various locations mainly in the northern hemisphere indicate that cooling occurred at different times in different regions, possibly because climatic and oceanic processes that link different regions or respond to perturbations and forcings are nonlinear, making it difficult to identify the ultimate cause of tropical reorganization, extratropical cooling, and Northern Hemisphere glaciation in the Pliocene (Ravelo et al., 2004; Raymo, 1994).

Regardless of the ultimate cause of cooling after the warm Pliocene, there is much we can learn from studying the early Pliocene warm period itself. Probably the most productive work in the future will come from paleoceanographers working together with climate theorists and modelers to understand the circumstances and conditions under which the long-term east-west tropical SST gradient and thermocline tilt can change, and the relationship of those changes to shorter-term climate variability. State-of-the-art atmosphere-ocean general circulation models predict a wide range of possibilities for how the mean state of tropical Pacific will change with greenhouse warming. However, if the models that simulate ENSO variability most accurately are to be believed, then the mean state should not change significantly (Collins, 2005). But do these same models have the ability to maintain reduced east-west SST and thermocline gradients as observed in the Pliocene? Attempts to model the warm Pliocene would be an excellent test of how well air-sea coupling, including parameterizations of physical processes, in the tropical Pacific is understood. Theoreticians could play a key role in developing strategies for data collection in order to constrain conditions in critical regions. Future observational studies documenting early Pliocene conditions must include (1) verification that SSTs in the western equatorial Pacific warm pool were not warmer than today; (2) reconstructions of latitudinal gradients that are also indicative of El Niño–like conditions; and (3) more detailed records of subsurface temperatures with more spatial resolution, because the three dimensional structure of the thermocline can lend insight into changes in surface currents and the wind field.

The fact that subsurface temperature changes, or thermocline conditions, were different in the early Pliocene warm period compared to today is an important clue that should be used to advance our understanding of how and why the mean state of tropical climate, and potentially global mean conditions and climate sensitivity, might change with time. In addition to the upwelling region in the eastern equatorial Pacific, subtropical upwelling regions in the Atlantic and Pacific were also warmer than present during the early Pliocene (Haywood et al., 2005; Herbert and Schuffert, 1998; Marlow et al., 2000), indicating that warm subsurface conditions due to a deeper thermocline were in fact a global characteristic of the warm Pliocene. This highlights the importance of future investigations of the processes that determine conditions in the global thermocline and their relevance for predicting global climate change.

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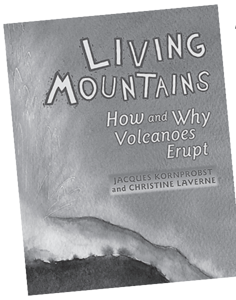

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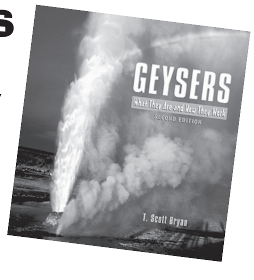

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