

Mid-Pliocene equatorial Pacific sea surface temperature reconstruction: a multi-proxy perspective

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The Mid-Pliocene is the most recent interval of sustained global warmth, which can be used to examine conditions predicted for the near future. An accurate spatial representation of the low-latitude Mid-Pliocene Pacific surface ocean is necessary to understand past climate change in the light of forecasts of future change. Mid-Pliocene sea surface temperature (SST) anomalies show a strong contrast between the western equatorial Pacific (WEP) and eastern equatorial Pacific (EEP) regardless of proxy (faunal, alkenone and Mg/Ca). All WEP sites show small differences from modern mean annual temperature, but all EEP sites show significant positive deviation from present-day temperatures by as much as 4.4°C. Our reconstruction reflects SSTs similar to modern in the WEP, warmer than modern in the EEP and eastward extension of the WEP warm pool. The east–west equatorial Pacific SST gradient is decreased, but the pole to equator gradient does not change appreciably. We find it improbable that increased greenhouse gases (GHG) alone would cause such a heterogeneous warming and more likely that the cause of Mid-Pliocene warmth is a combination of several forcings including both increased meridional heat transport and increased GHG.

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1. Introduction and background

Following two decades of intense study, the Mid-Pliocene (3.29–2.97 Ma) has emerged as a potential analogue for the Earth's future climate conditions near the end of this century (Hansen *et al.* 2006; Jansen *et al.* 2007). The Mid-Pliocene is an exceptional choice for palaeoclimatological studies aimed at better understanding the future for three main reasons. First, the Mid-Pliocene is geologically recent with a land–sea configuration and continental positions effectively the same as present. Second, the basic patterns of ocean circulation and faunal and floral distributions are similar, albeit somewhat displaced, relative to the present day. Finally, since many Mid-Pliocene species are extant, faunal and floral palaeotemperature proxies based upon modern core-top calibration, while near the limits of their respective methodologies, are still

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valid. The similarities between the Mid-Pliocene and the present allow us to understand the Pliocene palaeoclimate, from both a data and modelling perspective, in the framework of modern climate.

While unrivalled in its suitability, the Mid-Pliocene is not a perfect analogue for future climate. For example, orbital forcing during the Mid-Pliocene was not the same as today. Instead, Marine Isotope Stage 11 (MIS 11), a warm interglacial *ca* 420 to 400 ka, was characterized by a nearly identical orbital configuration to the present and near future. Temperatures then, however, were barely warmer than today. Also, while the Mid-Pliocene was significantly warmer than present, it was part of a long cooling trend (unlike the modern trend towards warmer conditions) that started at least one million years earlier and eventually led to the Late Pleistocene ice ages.

Despite these caveats, the Mid-Pliocene is the most recent interval of sustained global warmth that can be used to examine conditions predicted for the near future (Jansen *et al.* 2007). Since 1990, researchers have estimated the spatial and temporal distributions of Mid-Pliocene global warmth in a series of sub-global and global reconstructions of sea surface temperature (SST) as part of the US Geological Survey Pliocene Research, Interpretation, and Synoptic Mapping (PRISM) Project (See Dowsett & Poore 1991; Dowsett *et al.* 1994, 1996, 1999, 2005; Dowsett 2007a). These reconstructions, unique in their spatial coverage of a defined warm interval, have been used in a series of modelling experiments to better understand the features of a warmer world (e.g. Chandler *et al.* 1994; Sloan *et al.* 1996; Haywood *et al.* 2000; Haywood & Valdes 2004; Jiang *et al.* 2005; Barreiro *et al.* 2006).

One area under-represented in PRISM reconstructions has been the equatorial Pacific Ocean. Previous PRISM global SST reconstructions have few data points in the low-latitude Pacific and none in the eastern equatorial Pacific (EEP). In these reconstructions, the 0°C anomaly found in the western equatorial Pacific (WEP) was extended to the EEP and resulted in a strong east–west surface temperature gradient similar to modern circulation (Dowsett *et al.* 1999, 2005). However, geochemical proxies of Pliocene SST from the present-day upwelling areas off the west coast of South America suggest warmer-than-present surface conditions during the Mid-Pliocene (Ravelo *et al.* 2004; Wara *et al.* 2005; Dekens *et al.* 2007). Also, coupled ocean–atmosphere general circulation models (GCM) retrodict warmer conditions throughout the equatorial Pacific during the Mid-Pliocene, strongly suggesting a response to increased greenhouse gases (GHG), relative to pre-industrial concentrations (Haywood & Valdes 2004). Initial faunal data from the EEP indicate warmer-than-present conditions and a reduced east–west SST gradient in the equatorial Pacific, in agreement with the majority of geochemical data (Dowsett 2007a). Faunal data from the WEP indicate Mid-Pliocene temperatures essentially identical to the present, although minor warming of the WEP warm pool cannot be ruled out (Dowsett 2007b).

The spatial pattern of Mid-Pliocene climate conditions is similar in many ways to the pattern of effects presently attributed to the El Niño–Southern Oscillation phenomenon (Molnar & Cane 2002). The Mid-Pliocene may, then, represent the transition from the warm equatorial conditions of the Early Pliocene to the beginning of upwelling of cooler waters, the effects and feedbacks of which eventually led to Late Pleistocene glaciation (Federov *et al.* 2006). An accurate

spatial representation of the low-latitude surface ocean then takes an added importance in the quest to understand past climate change in the light of forecasts of future change.

The purpose of this paper is threefold. First, we examine the newest faunal data from the EEP and WEP to determine what if any SST changes, relative to present day, can be documented for the Mid-Pliocene. Second, we synthesize these new faunal data with existing alkenone and Mg/Ca SST proxy data from the equatorial Pacific to revise the PRISM2 reconstruction. These revised low-latitude data will form the cornerstone of the new PRISM3 global SST reconstructions. Finally, we compare the resulting Mid-Pliocene equatorial Pacific SST reconstruction with modern El Niño conditions in an effort to understand the palaeoceanographic implications.

(a) Oceanographic setting

Surface circulation in the tropical Pacific Ocean is dominated by the westward flowing South Equatorial Current and North Equatorial Current, and by the eastward flowing Equatorial Counter Current (figure 1). Two features of the equatorial Pacific oceanography are particularly relevant to this study. The first is the existence of the WEP warm pool. This is a region in the western Pacific where temperatures reach close to 30°C and vary little from season to season (figure 2). By contrast, low-latitude land areas reach maximum surface temperatures approaching 50°C. While there is no absolute limit to seawater temperature, we hypothesize that the 30°C maximum is a function of the feedback between warm water, evaporation/precipitation, atmospheric water vapour, cloud formation and associated albedo changes. The presence of the warm pool and its persistence over time, and between climate extremes (Dowsett 2007b), has important implications for palaeoclimate studies.

The second important oceanographic feature is the SST gradient between the western warm pool region and the EEP. Today, the thermocline is shallower in the eastern Pacific (approx. 50 m) than it is in the west (approx. 200 m). Ekman-type upwelling along the coast of South America and equatorial upwelling due to divergence extending from east to west across the equatorial region (figure 2) deliver relatively cold water from a depth of approximately 200 m to the surface. This creates the strong east–west SST gradient in the tropical Pacific. Every 4–7 years, the thermocline deepens in the east, and upwelling delivers warmer water to the surface resulting in a much weaker east–west SST gradient. This change, a phenomenon of El Niño, has significant impacts on weather conditions around the world. The presence of El Niño and its relative frequency at times in the past are relevant to an understanding of Pliocene warmth and to the dynamics of pre-Pleistocene climate change.

2. Materials and methods

Eleven marine localities were examined to infer low-latitude Pacific sea surface conditions during the Mid-Pliocene PRISM interval (3.29–2.97 Ma) (figure 1, table 1). Magnetostratigraphic, oxygen isotopic and biochronologic data available at each site were calibrated to the Berggren *et al.* (1995) time scale for correlation purposes. Details of the chronology for the PRISM interval can be

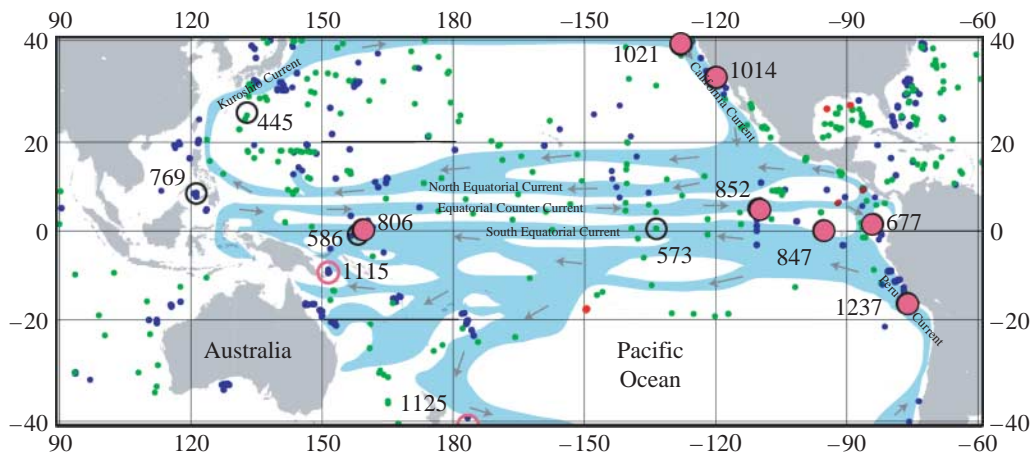


Figure 1. Core locality map showing idealized surface flow in the low-latitude Pacific Ocean. Sites used in the PRISM2 reconstruction are shown as open black circles while new sites are shown as filled pink circles. Open pink circles indicate other sites discussed in the text, and smaller green, blue and red dots represent existing DSIP, ODP and IODP sites, respectively.

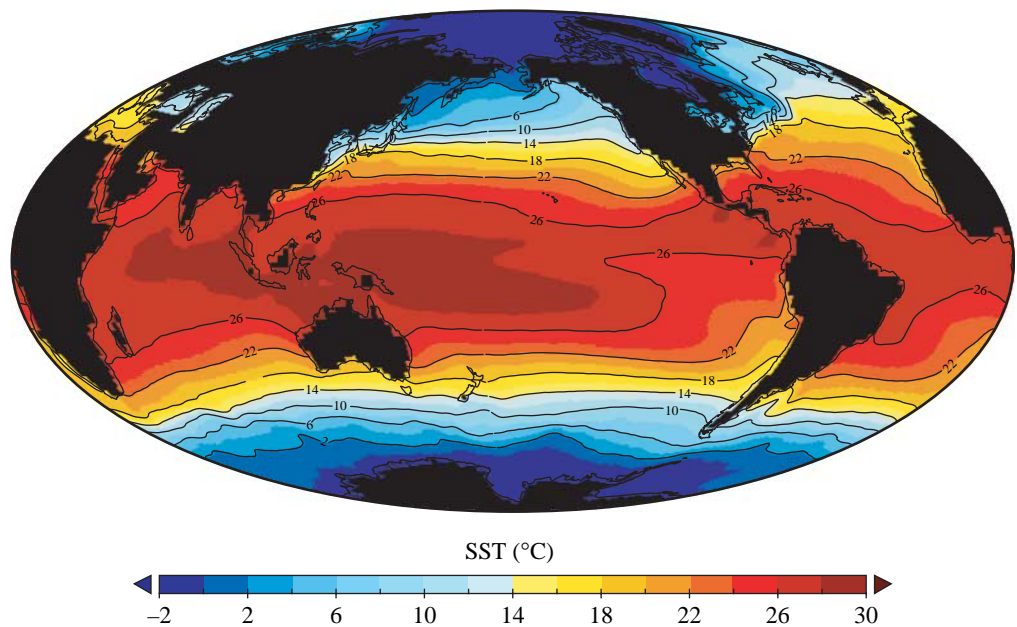


Figure 2. Modern mean annual SST. WEP warm pool is shown by large pod of 30°C water in the western Pacific and Indian Ocean.

found in Dowsett *et al.* (2005) and Dowsett & Robinson (2006, 2007). Throughout this paper, the term ‘Mid-Pliocene’ refers to the PRISM interval. Much of the palaeoenvironmental data synthesized here come from previous publications (table 1). Faunal processing and analysis methods refer to all core sites with faunal SST estimates. Descriptions of geochemical techniques are

Table 1. Site data and Mid-Pliocene SST estimates.

leg	site	latitude	longitude	SST estimate	proxy ^a	primary source
58	445	25.52	133.20	26.3	F	Dowsett & Robinson (1998)
85	573	0.48	-133.30	24.7	R	Hays <i>et al.</i> (1989)
89	586	-0.48	158.48	29.2	F	Jenkins (1992 <i>a,b</i>)
111	677	1.20	-83.74	27.4	F	Robinson <i>et al.</i> (2008 <i>a</i>)
				27.5	A	Robinson <i>et al.</i> (2008 <i>a</i>)
124	769	8.78	121.28	28.1	F	Dowsett & Robinson (1998)
130	806	0.32	159.35	29.0	F	Andersson (1997)
				30.3	M	Wara <i>et al.</i> (2005)
138	847	0.18	-95.32	26.9	F	Dowsett & Caballero (2007)
				26.9	A	Dekens <i>et al.</i> (2007)
				26.9	M	Wara <i>et al.</i> (2005)
138	852	5.28	-110.07	29.4	F	this study
167	1014	32.83	-119.98	24.0	A	Dekens <i>et al.</i> (2007)
167	1021	39.09	-127.78	21.5	F	Dowsett & Poore (2000)
202	1237	-16.00	-76.37	24.1	F	Caballero & Dowsett (2008)
				23.8	A	Dekens <i>et al.</i> (2007)
				21.7	M	Wara & Ravelo (2006)

^aF, foraminiferal assemblage; R, radiolarian assemblage; A, alkenone unsaturation index; M, foraminiferal (*Globigerinoides sacculifer*) Mg/Ca.

generic. Inter-laboratory differences due to sample preparation and analysis are potentially significant, and the reader is referred to the appropriate publications for complete information on specific techniques used for the sites listed in table 1.

(a) Palaeontological methods

Samples processed for planktic foraminifer analysis were oven dried at 50°C or less. Dried bulk samples were disaggregated in 250 ml of warm tap water with approximately 2 ml of dilute sodium hexametaphosphate (5 g per litre of water). The samples were agitated for 1 hour at room temperature and then washed over a 63 µm sieve using a fine spray. The coarse fraction was dried in an oven at 50°C or less. Some samples required an additional wash cycle to obtain clean specimens. A split of 300–350 planktic foraminifer specimens was obtained from the size fraction of 150 µm or more using a sample splitter. Specimens were sorted, identified and glued to 60-square micropalaeontological slides. In general, our taxonomic concepts follow Parker (1962, 1967) and Blow (1969). Exceptions to their practices are documented in Dowsett & Robinson (2007).

Applicable quantitative palaeontological methods vary with location and fossil group in the low-latitude Pacific (Dowsett 2007*b*). The relative scarcity of well-preserved (in terms of carbonate) core-top samples in the Pacific limits the application of Pacific-based foraminiferal transfer functions (Thompson 1976; Anderson *et al.* 1989; Andersson 1997; Dowsett & Robinson 1998; Pflaumann & Jian 1999; Ujiie & Ujiie 2000; Dowsett 2007*a,b*). The modern analogue technique (MAT) can be applied to planktic foraminifer assemblages in the EEP owing to upwelling-induced cool temperature conditions at the surface. In the WEP warm

pool, MAT is of limited value since modern temperatures are approximately 30°C and therefore at the upper limit of the calibration dataset. Hence, Mid-Pliocene SST estimates near 30°C are inconclusive and could represent warmer temperatures than exist in the modern ocean (Dowsett 2007b).

MAT uses a distance measure between a target (fossil) sample and the nearest modern analogues in a calibration dataset to estimate past conditions (Dowsett & Robinson 1998; Dowsett & Poore 1999; Dowsett 2007a,b). The squared chord distance (SCD) metric

$$d_{ij} = \sum_k \left(p_{ik}^{1/2} - p_{jk}^{1/2} \right)^2,$$

where d_{ij} is the SCD between two multivariate samples i and j , and p_{ik} is the proportion of species k in sample i , is used to compare Pleistocene and Pliocene target samples to a 510-sample modern database (Dowsett 2007b).

In general, methods using siliceous fossil groups have more success in the Pacific (due to lack of carbonate preservation) and have been used extensively in estimating Mid-Pliocene conditions. Factor analytic transfer functions were applied to Pliocene radiolarian assemblages at site 573 to produce SST estimates (Hays *et al.* 1989).

(b) Geochemical and biochemical methods

The primary geochemical or biochemical SST proxies that produce useful Mid-Pliocene results in the low-latitude Pacific are foraminiferal Mg/Ca and alkenone unsaturation indices. These proxies have been used to estimate equatorial Pacific SST (Ravelo *et al.* 2004; Rickaby & Halloran 2005; Wara *et al.* 2005; Dekens *et al.* 2007) and represent the basis for a re-evaluation of the PRISM faunal-based reconstruction.

The ratio of magnesium to calcium in foraminiferal tests varies exponentially with temperature (e.g. Nürnberg *et al.* 1996; Lea *et al.* 1999; Mashiotta *et al.* 1999) and thus allows for temperature estimation of the water mass at the time and water depth of calcification. The generalized methodology begins with picking a number of individual tests from a particular species and size fraction. Mg/Ca cleaning procedures vary from laboratory to laboratory but generally include crushing tests to open chambers, multiple rinses/sonications with deionized water and methanol, and reductive and oxidative cleaning with intermittent sonication, each followed by deionized water rinses, weak acid rinses/leaches, final deionized water rinses, dissolution, centrifuging, decanting and analysis. All Mg/Ca data used here are from Wara *et al.* (2005) and Wara & Ravelo (2006). The authors estimated SST by applying the species-specific calibration equation of Dekens *et al.* (2002) to Mg/Ca values of *Globigerinoides sacculifer* (without the final sac-like chamber).

Alkenones are produced by a few species of haptophyte algae that live in the near-surface ocean. The $U_{37}^{k'}$ index has been linearly calibrated to ocean near-surface temperature (Prah *et al.* 1988; Müller *et al.* 1998; Conte *et al.* 2006) and can be used to estimate mean annual SST. In general, organics were extracted from sediment samples and analysed using a gas chromatograph. Peak areas of C_{37:2} and C_{37:3} alkenones were used to calculate the alkenone unsaturation ($U_{37}^{k'}$) index. All reported $U_{37}^{k'}$ SST estimates in this study were obtained using the

Table 2. Western equatorial Pacific SST anomalies for PRISM3 reconstruction.

site	modern SST ^a	modern SST ^b	faunal anomaly	alkenone anomaly	Mg/Ca anomaly
445	24.7	25.6	1.6	–	–
586	29.1	29.2	0.1	–	–
769	27.8	28.7	0.3	–	–
806	29.1	29.2	–0.1	–	1.1

^aReynolds & Smith (1995).^bLevitus & Boyer (1994).

Prahl *et al.* (1988) calibration curve. Reproducibility of analysis was better than $\pm 0.005 U_{37}^{k'}$ units, which corresponds to a temperature uncertainty of $\pm 0.2^\circ\text{C}$. Separation and quantification of alkenones from site 677 were performed at Brown University; alkenones from sites 847, 1014 and 1237 were analysed at the University of California Santa Cruz (see Dekens *et al.* 2007).

3. Results

Estimates of Mid-Pliocene SST based upon faunal assemblages, Mg/Ca and alkenones are presented in table 1. These estimates were obtained using the warm-peak averaging technique (Dowsett 2007a). For Mg/Ca and alkenone methods, warm peaks were chosen from the mean annual temperature time series. For faunal assemblage estimates, which are traditionally reported as cold season and warm season estimates, warm peaks were identified in the cold season time series (following PRISM2 methodology), and then averaged with the associated warm season value to create a mean annual SST. Thus the PRISM2 reconstruction is driven by cold season warm events. The Mid-Pliocene anomalies (Pliocene minus appropriate (depending upon proxy) modern value) for the western Pacific and eastern Pacific are shown in tables 2 and 3, respectively. Faunal assemblage-based anomalies are calculated using the modern mean annual SST database of Reynolds & Smith (1995), and Mg/Ca- and alkenone-based anomalies use Levitus & Boyer (1994) because these are the modern temperature datasets used in calibrating the unique temperature equations. Faunal assemblage-based SST time series for sites 677, 847, 852 and 1237 and the alkenone-based SST series from site 677 are illustrated in figure 3.

(a) Western Pacific

The western Pacific reconstruction is anchored at site 806 by the analysis of planktic foraminifer assemblages (Andersson 1997; Dowsett 2007b) and Mg/Ca (Wara *et al.* 2005). Faunal assemblage-based estimates show no significant change in either season from present-day conditions in the WEP warm pool. Mg/Ca estimates at site 806 (Wara *et al.* 2005) report warmer average conditions than the assemblage-based estimates ($+1.1^\circ\text{C}$ relative to present-day mean annual temperature) at a much lower stratigraphic resolution. Sites 586

Table 3. Eastern equatorial Pacific SST anomalies for PRISM3 reconstruction.

site	modern SST ^a	modern SST ^b	faunal anomaly	alkenone anomaly	Mg/Ca anomaly
573	25.3	25.9	-0.6	-	-
677	25.9	25.6	1.5	1.9	-
847	24.1	24.4	2.8	2.5	2.5
852	26.9	27.0	2.5	-	-
1014	16.3	16.1	-	7.9	-
1021	14.3	14.5	7.2	-	-
1237	19.7	20.0	4.4	3.8	1.7

^aReynolds & Smith (1995).

^bLevitus & Boyer (1994).

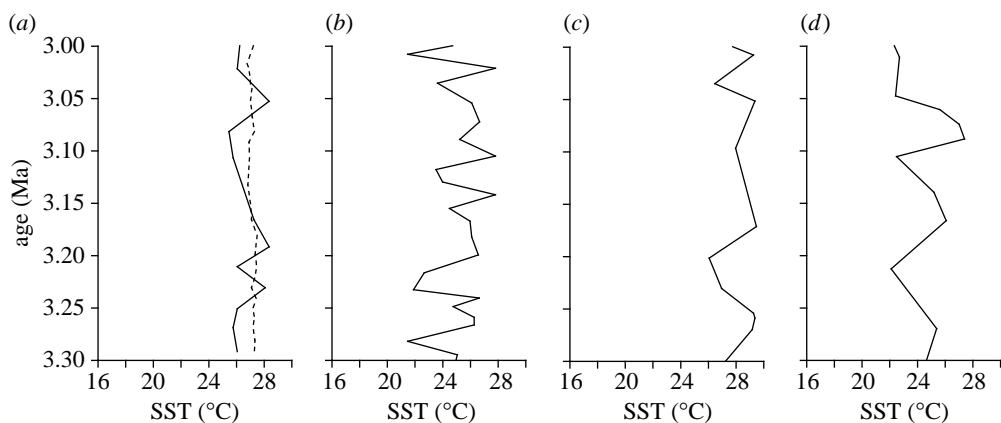


Figure 3. New Mid-Pliocene mean annual SST estimates. Solid lines indicate planktic foraminifer assemblage-based estimates; dashed line indicates alkenone-based estimates. (a) ODP 677; (b) ODP 847; (c) ODP 852; (d) ODP 1237.

and 806 are essentially at the same location, and faunal data show nearly identical results. Planktic foraminifer assemblage-based SST estimates at site 769, just north of the equator in the Sulu Sea (figure 1), show at most 0.3°C warming over the present mean conditions (Dowsett & Robinson 1998).

Site 806 faunal data were re-analysed in detail by Dowsett (2007b). The planktic foraminiferal fauna at site 806 is dominated by thermophilic taxa (*Dentoglobigerina altispira*, *Globigerinoides ruber*, *G. sacculifer* and *G. obliquus*). Some samples within the Mid-Pliocene interval of site 806 show increased similarity to modern samples from regions with a strong seasonal productivity signal (Dowsett 2007b). This suggests, at least at times within the Mid-Pliocene, nutrient levels higher than those found in the WEP today.

In a supporting study, Siesser (2001) recorded several cool events at site 1115 (less than 10° S in the WEP) that punctuated generally warm and stable conditions during the Early Pliocene. An interval of warm sea surface conditions near 3.2 Ma is presumably correlative with the PRISM warm interval. The nanofossil-based SST method used in this study provides relative temperature (cooling versus warming) and is therefore a qualitative aid in reconstructing

Mid-Pliocene SST. However, the generally warm and stable conditions at site 1115 show good agreement with the other available data from the region and suggest a prolonged interval of warmth, essentially equivalent to modern conditions, in the WEP.

(b) *Eastern Pacific*

Until now, no planktic foraminifer-based SST estimates existed for the Mid-Pliocene in the EEP. We present here new faunal-based estimates from sites 677, 847, 852 and 1237 as well as a new alkenone-based SST record from site 677 (figure 3). At site 1237, approximately 16° S in the Peru Current, warming is documented in faunal assemblages, alkenone and Mg/Ca data (+4.4, +3.8 and +1.7°C relative to modern mean annual conditions, respectively). Although these anomalies vary in magnitude, each proxy indicates warmer conditions during the Mid-Pliocene. Closer to the equator, sites 847 and 852 show similar warming based upon analysis of the planktic foraminifer fauna: +2.8 and +2.5°C, respectively, relative to modern conditions. These results corroborate the Mg/Ca (+2.5°C) and alkenone (+2.5°C) estimates at site 847 (Wara *et al.* (2005) and Dekens *et al.* (2007), respectively). Site 677 indicates warming during the Mid-Pliocene of +1.9°C based upon alkenones and +1.5°C based upon foraminifer assemblages (Robinson *et al.* 2008a). Radiolarian-based SST estimates from site 573 in the central equatorial Pacific show conditions essentially similar to modern at -0.6°C relative to today (Hays *et al.* 1989).

Sites 677, 847, 852 and 1237 all contain Mid-Pliocene planktic foraminifer assemblages with increased abundances of high-nutrient indicators (*Neoglobobulimina*) relative to the quantities found in the WEP warm pool during the same time interval (Andersson 1997; Dowsett 2007b; Dowsett & Caballero 2007; Caballero & Dowsett 2008; Robinson *et al.* 2008a).

(c) *Extra-tropical regions*

Further north, off the coast of North America, the Pliocene planktic assemblage at site 1021 (Dowsett & Poore 2000) suggests that mean annual temperature may have been approximately 7°C warmer than today. Anomalies this large appear to be corroborated by alkenone-based SST estimates from nearby site 1014 that show mean annual temperatures within the PRISM interval (using peak warming procedures) of 7.9°C warmer than today (Dekens *et al.* 2007). While these California Margin sites are not tropical, they serve as additional examples, such as site 1237 off Peru and the other equatorial upwelling sites, of warmer water being upwelled at this time.

Sabaa *et al.* (2004) analysed the planktic assemblage from site 1125, located east of New Zealand on the Chatham Rise, in 1360 m of water. Applying peak averaging methodology (Dowsett 2007a) to the published site 1125, SST record reveals little to no change relative to present-day conditions during the Mid-Pliocene. Further study of the site 1125 assemblage data using the same faunal regrouping and RAM procedures applied to other Pacific cores in the PRISM reconstruction is necessary to interpret how this record fits with other western Pacific PRISM estimates.

4. Discussion

The SST anomaly values during the stratigraphically narrow PRISM interval show a strong contrast between the WEP and EEP regardless of proxy. All three sites within 20° latitude of the equator in the west (sites 586, 769 and 806) show small differences from present-day mean annual temperature, ranging from -0.1°C to 1.1°C and within the margin of error for each palaeothermometry method. By contrast, the values from all sites in the same latitude band in the EEP (sites 677, 847, 852 and 1237) show significant positive deviation from present-day conditions by as much as 4.4°C , resulting in a greatly reduced east–west surface temperature gradient.

(a) *Low-latitude heterogeneity*

The question of the magnitude of warming in low-latitude regions is critical to our understanding of the causes of Mid-Pliocene warming. We present the first low-latitude comparison of Mid-Pliocene SST estimates derived from different proxy methods. Robinson *et al.* (2008*b*) have shown the applicability of the multi-proxy technique at mid- to high-latitude Mid-Pliocene sites in the North Atlantic, and here we extend this technique to the low-latitude Pacific. Haywood *et al.* (2005) is often cited (eg. Haywood *et al.* 2007; Lawrence *et al.* 2007) as a comparison of the faunal assemblage and alkenone SST proxy techniques. In that paper, however, none of the sites chosen for *comparison* had estimates from both proxies; rather, alkenone estimates from a single location were compared with highly interpolated SSTs based upon widely separated PRISM core sites. In addition, while purportedly documenting warming in low-latitude regions, all but two of the sites used in Haywood *et al.* (2005) came from extra-tropical regions, and all were restricted to upwelling zones. The conclusion that PRISM SST fields are not compatible with the alkenone SST estimates is basically correct but is easily explained since, due to limitations in the proxy method, alkenone-derived SST estimates in the tropics are restricted to upwelling regimes, and PRISM, until now, had examined no sites in tropical upwelling regimes.

The results of this paper and all previous Mid-Pliocene multi-proxy analyses point to overwhelming concurrence: in low-latitude upwelling areas, clear evidence of warming exists; but in low-latitude areas away from upwelling, any warming is minimal.

Low-latitude data are critical to our understanding of the cause of Pliocene warmth. Dowsett *et al.* (1992) suggested, based upon the reduced Mid-Pliocene pole to equator surface temperature gradient (relative to today), that meridional ocean heat transport was the cause of Mid-Pliocene warming. Haywood *et al.* (2005) suggested that the gradient produced by a fully coupled ocean–atmosphere GCM and supported by alkenone SST analyses was more compatible with increased GHG as the cause of warming. Since the two studies looked at different parts of the Mid-Pliocene system, it is difficult to compare the results. In addition, $2\times\text{CO}_2$ experiments show similar warming at all latitudes, modified at high latitude by the removal of sea ice. Thus, we find it improbable that increased GHG would cause such a heterogeneous warming (only in upwelling areas) in the low-latitude regions. Furthermore, Dekens *et al.* (2007) have eloquently outlined the probability that upwelling still occurred during the

Mid-Pliocene but involved water decidedly warmer than at present. This suggests a different mechanism for the cause of the warmer water at depth and warrants a renewed investigation of high-latitude source waters. Ultimately, the cause of Mid-Pliocene warmth is still elusive but probably a combination of several forcings.

(b) *El Niño frequency*

The spatial pattern of surface temperature in the low-latitude Pacific during the Mid-Pliocene is remarkably similar to the pattern that occurs during present-day El Niño. While the concept of permanent El Niño (Ravelo *et al.* 2006) is convenient for comparisons, it probably does not serve as a true analogue. The stratigraphic resolution in this and any previous palaeoceanographic studies of the equatorial Pacific is not sufficient to resolve El Niño frequency. With the time-averaged signal inherent in core samples, it is more accurate to think of changes in the timing of El Niño-like conditions in terms of El Niño being more the norm than the quasi-periodic exception. Core-top assemblages in these regions are a time-averaged signal of modern conditions which, based upon historical records, are skewed towards non-El Niño conditions. Since our analyses are showing slightly warmer, nutrient-rich faunas, we conclude that the relative contribution of ‘normal’ fauna and El Niño-type faunas was different during the Mid-Pliocene. Thus, El Niño frequency was probably higher during the Mid-Pliocene than it has been over observational history, but perhaps not permanent.

Present-day El Niños are accompanied by a tilting of the equatorial Pacific east–west thermocline resulting in a thicker pod of warm near-surface water in the EEP than exists during non-El Niño years. Upwelling still occurs in the EEP during times of El Niño, but the source of the upwelled water is from above the thermocline rather than below it, and the upwelled water is depleted in nutrients. During the Mid-Pliocene, evidence exists for a similarly thick surface layer and a deeper thermocline in the EEP. Dekens *et al.* (2007), however, conclude that the water being upwelled during the Early Pliocene in the EEP was warm but nutrient-rich. Our faunal assemblage work confirms the existence of high-nutrient indicators at sites in the EEP, but further work is required to document changes in the source of the warm, nutrient-rich water.

As an example, Dowsett & Willard (1996) traced the water being upwelled in the Benguela System off southwest Africa to its source in the Southern Ocean. The upwelled waters were warmer and depleted of nutrients during the Mid-Pliocene relative to today because surface waters slightly warmer than at present surrounded the Antarctic continent, and diatom production was high over a broad area. Antarctic Intermediate Water (AAIW) leaving the Southern Ocean was depleted of nutrients by diatoms near the edge of the Antarctic sea ice, and productivity was low when the AAIW upwelled in the Benguela System. Today, cooler, higher nutrient waters characterize upwelling conditions in the Benguela System because diatom productivity off Antarctica is restricted due to the northward migration of the sea ice boundary and the polar front. The aerial extent of productivity is much smaller than it was during the Mid-Pliocene, resulting in an underusage of nutrients and, therefore, higher nutrient content of AAIW.

Source waters for the upwelling in the modern EEP are from southern subtropical regions and Subantarctic Mode Water (Kessler 2006; Robinson *et al.* 2007). Additional work documenting changes in different water masses and their source regions during the Mid-Pliocene is necessary to understand the mechanisms causing the upwelling of warm, nutrient-rich water in the EEP. This in turn will allow better understanding of ocean circulation patterns and heat distribution during the Mid-Pliocene.

(c) *Palaeoclimate reconstruction, future climate prediction*

Our limited understanding of future climate comes primarily from GCM experiments paired with studies of past analogous warm climates. Future climate projections based upon an ensemble of GCMs point to an Earth with a mean global temperature 2–3°C warmer than the present by the end of the century (Jansen *et al.* 2007). Analysis of Mid-Pliocene palaeoclimate data suggests the Earth was 2–3°C warmer than the present during that time. Training coupled ocean–atmosphere models on Mid-Pliocene palaeoclimate data should help to improve the quality of the models and provide insight into the causes of Mid-Pliocene warmth by analysing possible causes as potential drivers of future climate. It is important, therefore, to continually improve palaeoclimate reconstructions as new data become available.

To this end, this work has led directly to the improvement of the PRISM2 reconstruction by enriching the PRISM dataset with palaeoclimate data from the EEP where before there was none. Figure 4 presents the newly improved PRISM3 reconstruction as well as the PRISM3 anomaly for comparison. The PRISM3 reconstruction reflects the above discussion by showing SSTs similar to modern in the WEP, warmer than modern SSTs in the EEP upwelling zones (figure 2), and an eastward extension of the WEP warm pool. The east–west equatorial SST gradient is decreased in PRISM3, but the PRISM2 equator-to-pole gradient is altered only slightly in response to the increased SSTs in the EEP.

5. Conclusions

The results presented here confirm a reduced east–west surface temperature gradient during the Mid-Pliocene, similar to a modern El Niño, already established by long Mg/Ca and alkenone time series (Ravelo *et al.* 2006). More importantly, we provide the means for an equatorial Pacific spatial reconstruction encompassing multiple localities focused on a very brief interval of time. In addition, the multivariate analysis of faunal assemblage data provides additional information regarding Mid-Pliocene conditions.

We present the first low-latitude comparison of Mid-Pliocene SST estimates derived from different proxy methods. The results of this paper indicate stability in tropical regions away from upwelling zones with concomitant warming in areas of upwelling. This heterogeneous warming at low latitudes does not appear to endorse increased GHG as the driver for Mid-Pliocene warming. Rather, a combination of increased GHG and enhanced meridional heat flux, and perhaps still unknown processes, may be the forcing for Mid-Pliocene conditions and therefore needs to be investigated for its role in future climate scenarios.

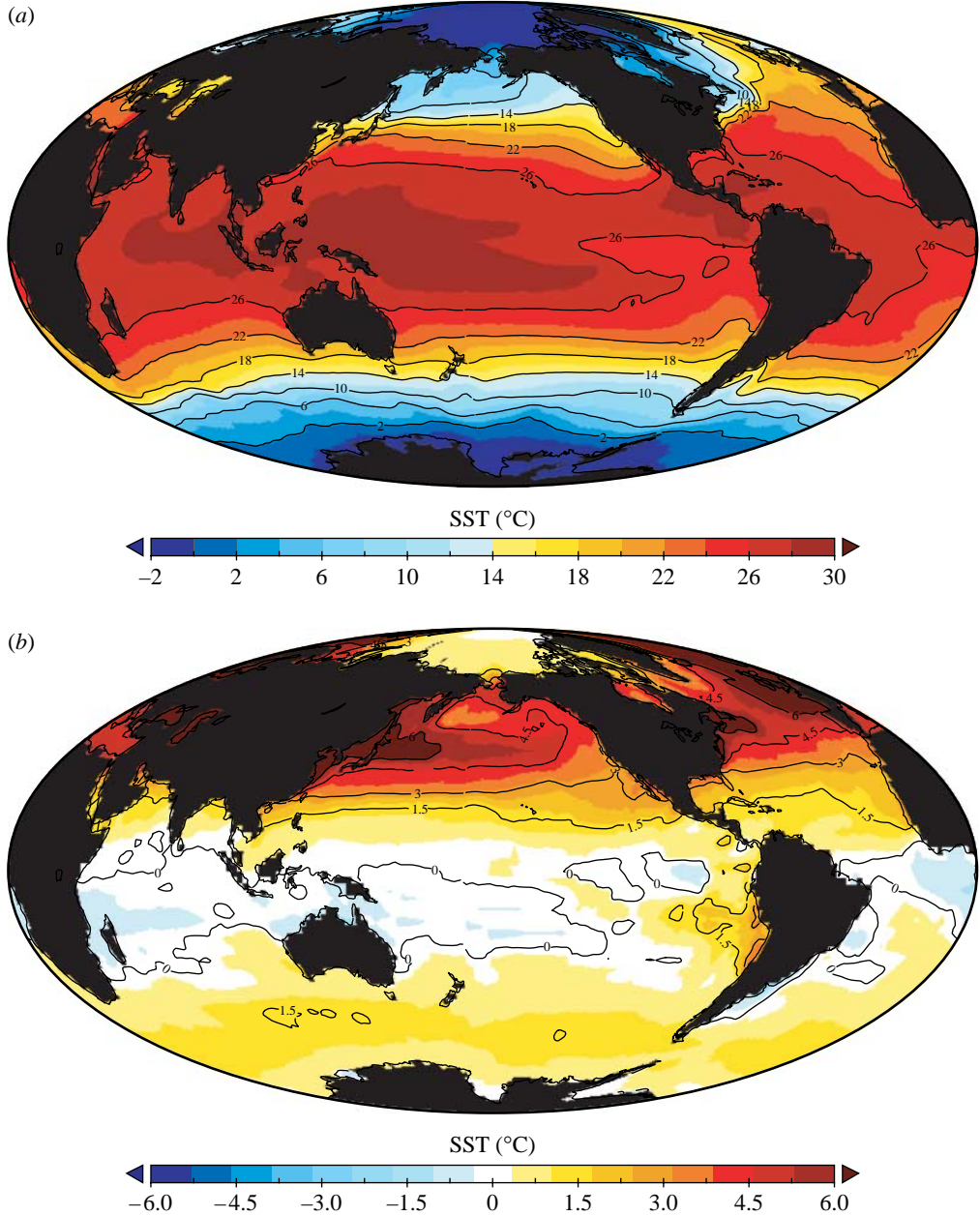


Figure 4. (a) New PRISM3 mean annual SST reconstruction map and (b) Mid-Pliocene PRISM3 SST anomaly map (PRISM3 minus modern) for comparison.

In the WEP, Mid-Pliocene faunal assemblages show no significant change from present-day SST but suggest nutrient levels higher than those found today. By contrast, multiple lines of evidence support warming of the EEP during the Mid-Pliocene, and faunal assemblage data show a persistence of upwelling of warm, nutrient-rich water. Extra-tropical California Margin sites serve as additional examples of warmer water being upwelled at this time. While these extra-tropical

sites are not necessarily governed by the same processes as those in the EEP, additional work documenting changes in different water masses and their source regions is necessary to understand the mechanisms causing the upwelling of warm, nutrient-rich water in the EEP and elsewhere. This in turn will allow better understanding of ocean circulation patterns and heat distribution during the Mid-Pliocene.

As part of the PRISM3 reconstruction, we have revised the PRISM2 low-latitude Pacific SSTs to fit all available palaeoceanographic data. The stability of the WEP warm pool is clearly documented in this and other studies of the Mid-Pliocene. The recent re-analysis of Mid-Pliocene assemblages from site 806 and other sites in the WEP reinforces the interpretation of a spatially expanded WEP warm pool with temperatures unchanged, or possibly slightly elevated, relative to present-day and warmer than modern SSTs in modern upwelling zones in the EEP. The east–west equatorial SST gradient is decreased in PRISM3, but the pole to equator gradient does not change appreciably.

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