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Key Points:
- Pliocene equatorial Pacific sea surface temperatures were warmer than modern everywhere, with largest anomalies in the east
- A mean El Niño-like state, characterized by a reduced zonal sea surface temperature difference, existed in the Pliocene equatorial Pacific
- Pliocene Indian Summer Monsoon is estimated to have been ~20–40% weaker than modern

Supporting Information:
- Supporting Information S1
- Table S1

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Multiproxy Reduced-Dimension Reconstruction of Pliocene Equatorial Pacific Sea Surface Temperatures

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Abstract A controversial aspect of the Pliocene climate system is a posited permanent sea surface temperature (SST) distribution resembling that during El Niño events, which is largely inferred from sea surface temperatures reconstructed from several sites in the equatorial Pacific. We utilize a reduced-dimension methodology on a compilation of previously published multiproxy (Mg/Ca, $U^{k'}_{37}$, TEX_{86}, and foraminifer assemblages) Pliocene SST records from the equatorial Pacific to reconstruct spatial and temporal snapshots of SST anomalies and a time series of Niño indices from 5 to 1 Ma. The use of multiple proxies increases the number of study sites and thereby improves the robustness of the reconstruction. We find that the early Pliocene equatorial Pacific was characterized by a reduced zonal SST difference due to minimal change in the west and extreme warmth in the east which peaked at 4.3 Ma. The intensity of this mean El Niño-like SST state then gradually diminished toward modern conditions. We also use the Pliocene Niño 4 time series to estimate the past strength of Indian Summer Monsoon given the modern correlation of it to the Niño 4 index. Results indicate the monsoon was weaker throughout the study interval with weakest conditions (~37% less rainfall than modern) occurring at 4.3 Ma, congruent with regional proxy records. In summation, this reduced-dimension approach spatially and temporally resolves the warm mean state of the Pliocene equatorial Pacific and has numerous applications to inferences of paleoclimate conditions in distal regions teleconnected to El Niño today.

Plain Language Summary The Pliocene Epoch (5.3–2.6 million years ago) is the most recent time interval in Earth history when atmospheric carbon dioxide concentrations may have been similar to today and the continents were in their current configuration. For these reasons, Pliocene paleoclimate reconstructions are considered to be a useful indicator of conditions expected by the end of the 21st century. Several marine-derived Pliocene reconstructions from the equatorial Pacific suggest a sea surface temperature (SST) distribution that resembles SSTs during El Niño events today. El Niño events have widespread impacts including reduced marine productivity in the eastern equatorial Pacific and weakened Indian Summer Monsoon. Insights into Pliocene El Niño-like SSTs are typically based on paleoclimate reconstructions from a few sites that are then used to infer regional conditions. In this study, we apply a statistical method to a compilation of nine Pliocene SST records across the equatorial Pacific to fill in the spatial gaps in the paleotemperature reconstructions. Our maps of reconstructed Pliocene SSTs reveal that the eastern equatorial Pacific was 3–6 °C warmer than today, which is consistent with a mean El Niño-like state. Given the modern El Niño-Indian Summer Monsoon relationship, we estimate that Pliocene monsoon was ~20–40% weaker than today.

1. Introduction

The Pliocene (ca. 5.3–2.6 million years ago) is the most recent time interval in Earth history when global climate was warmer than the present (e.g., Fedorov et al., 2013; Salzmann et al., 2011) and when atmospheric CO_2 concentrations may have been comparable to those of the modern 400-ppm world (Martínez-Botí et al., 2015; Pagani et al., 2010; Seki et al., 2010). For these reasons, the Pliocene is considered a potential analog for climate conditions predicted for the latter part of this century (Crowley, 1996; Dowsett et al., 1996; Dowsett & Robinson, 2009). Not surprisingly, Pliocene climate model simulations with concentrations of CO_2 greater than those of pre-industrial time (Burls et al., 2017; Chandan & Peltier, 2018, 2017; Haywood et al., 2010, 2013; Lunt et al., 2008; Salzmann et al., 2013) and/or with assumed or simulated reduced northern hemisphere ice cover (e.g., Feng et al., 2017; Haywood & Valdes, 2004; Howell et al., 2016) lead to higher temperatures at mid and high latitudes. Other model runs, however, that exploit perturbations to equatorial Pacific SSTs can also lead to warmer midlatitude and high-latitude (e.g., Barreiro et al., 2005; Brierley & Fedorov, 2010; Burls & Fedorov, 2014a, 2014b; Goldner et al., 2011; Shukla et al., 2009, 2011; Vizcaíno et al., 2010). Thus, mimicking global warmth alone does not provide a good test of what processes made the Pliocene warmer than pre-industrial time (e.g., Fedorov et al., 2006), and investigations of regional differences in climate are needed.

Previous Pliocene reconstructions indicate that El Niño-like conditions prevailed across the equatorial Pacific, as evidenced by anomalously warm SSTs and a deep thermocline in the east (Cannariato & Ravelo, 1997; Chaisson & Ravelo, 2000; Dekens et al., 2007, 2008; Fedorov et al., 2013; Ford et al., 2012, 2015; Lawrence et al., 2006; Molnar & Cane, 2002; Philander & Fedorov, 2003; Ravelo et al., 2006; Seki et al., 2012; Wara et al., 2005), high sea surface salinities in the west (Wycech, 2017), and a relatively shallow thermocline in the west (Chaisson & Ravelo, 2000). Furthermore, global Pliocene temperature and precipitation patterns resemble those produced during the strongest El Niño event in the historical record (1997–1998; Molnar & Cane, 2007). Modern El Niño events occur every 2–7 years when the atmospheric Walker Circulation relaxes (Bjerknes, 1969; Julian & Chervin, 1978). Such interannual El Niño events, however, cannot be explicitly resolved on geologic timescales because samples from the deep-sea climate archive are temporally blended by slow sedimentation and bioturbation (Anderson, 2001; Goreau, 1977; Schiffelbein, 1984). Thus, Pliocene SST reconstructions in the equatorial Pacific reflect mean conditions rather than the quasiperiodic El Niño events that occur today.

Inferences of the mean state of Pliocene El Niño are typically derived from reconstructions at strategically located sites across the equatorial Pacific. Inferring regional ocean conditions from one spatial data point is risky, however. Proxies used for the reconstruction are susceptible to local perturbations in hydrography or sedimentary preservation. For example, down-core variations in the preservation of the shells of foraminifera, carriers of the Mg/Ca paleotemperature proxy, can produce temporal shifts in reconstructed SST records that are unrelated to ocean warming or cooling (Wycech et al., 2018). Furthermore, local changes in upwelling or turbidity may alter the depth habitat of the organisms that carry the proxies assumed to record sea surface conditions (Schiebel et al., 1997; Schmuker, 2000; Schmuker & Schiebel, 2002; Wycech, 2017). On longer time scales such as that of the Pliocene, some sites may also record the influences of local tectonic events, such as the emergence of the Galapagos Islands on both sides of the equator (Karnauskas et al., 2017), which may lead to erroneous inferences in regional SST change through time.

To alleviate these issues, several previous studies have applied alternative statistical approaches to reconstruct time series (e.g., Kaufman et al., 2009; Lee et al., 2008; Li et al., 2010; Mann et al., 2008; Moberg et al., 2005) or full field maps (e.g., Cook et al., 1999; Gill et al., 2016; Gill et al., 2016; Kaplan et al., 1998; Luterbacher et al., 2004; Mann et al., 1998, 2008; Tierney et al., 2019; Tingley & Huybers, 2010) of climate conditions in the geologic past. Similarly, in this study, we compiled previously published multiproxy SST records spanning 5–0 Ma across the equatorial Pacific and used principal component analysis (PCA) to reconstruct well-resolved maps of Pliocene SST anomalies. Relative to typical methods used to infer conditions from a few records, our statistical approach provides a more rigorous assessment of the mean strength of the Walker Circulation during the Pliocene. Furthermore, it allows us to calculate Niño indices and thereby estimate the strength of Indian Summer Monsoon.

2. Data

Our application of PCA uses the relationship between the contemporary SSTs in the full field (gridded map, Figure 1b) and limited field (discrete spatial points, Figure 1c) to reconstruct the paleo-SST full field from only the limited field paleo-SST data set.

2.1. Contemporary Data

Monthly SSTs from the equatorial Pacific region from 16°S to 16°N and 100°E to 60°W, gridded 2° × 2°from 1854 to 2018 are sourced from the NOAA National Climatic Data Center (NCDC) Extended Reconstruction Sea Surface Temperature (ERSST) version 3b data set (Smith et al., 2008). Monthly SST anomalies were

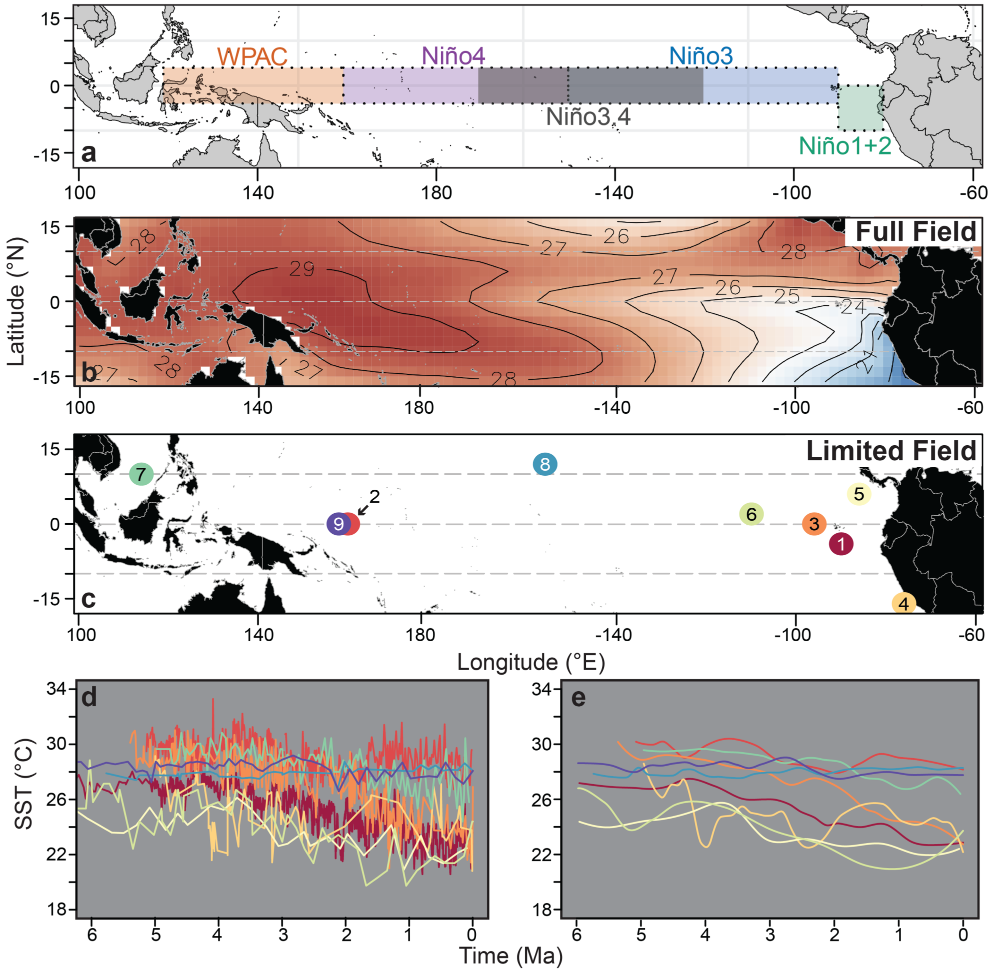

Figure 1. Equatorial Pacific maps of (a) Niño Index regions (see section 3.1 for coordinates), (b) mean SSTs of the contemporary full field (1854–2018), and (c) the limited field sites with Pliocene SST records. (d) Raw SST time series. (e) Smoothed SST records using a second order local polynomial with a local neighborhood of 20% nearest data points.

calculated using the 1981–2010 climatology and averaged from May to the following April to produce annual averages. The averaging over May to April enables us to capture the annual El Niño Southern Oscillation (ENSO) signal as it is strongest during boreal winter.

2.2. Paleo-SST Data

We compiled Pliocene SST records from four proxies: Mg/Ca, $U^{k'}_{37}$, TEX_{86}, and foraminifer assemblages (supporting information, Table S1). Culturing experiments performed on living planktic foraminifera have shown that the magnesium content of their shells increases exponentially with increasing temperatures (e.g., Lea et al., 1999; Nürnberg et al., 1996). Alkenones are organic molecules produced by some species of marine phytoplankton (coccolithophores) and record temperatures by their degree of unsaturation (number of double bonds connecting carbon atoms). Specifically, the Unsaturation Index is defined by the ratio between the diunsaturated ($C_{37:2}$) alkenones to the sum of diunsaturated and triunsaturated ($C_{37:3}$) alkenones, $U^{K'}_{37} = C_{37:2}/(C_{37:2} + C_{37:3})$ (Brassell et al., 1986; Marlowe et al., 1984; Prahl & Wakeham, 1987; Volkman et al., 1980). The TEX_{86} proxy is based upon the temperature correlation with the relative abundances of 86-carbon glycerol dialkyl glycerol tetraethers synthesized by archaea from the *Thaumarchaeota* phylum (Kim et al., 2008; Schouten et al., 2002). An ecological approach to paleotemperature reconstruction is transfer function analysis using planktic foraminifer assemblages (Imbrie & Kipp, 1971). This method uses abstract factor analysis on foraminifer census data from core-top samples to determine the relative contribution, or factor, of each species to the assemblage. These factors are then input into multiple regression to calibrate a transfer function that is applied to down-core assemblage data and used to reconstruct past SSTs.

Although SST records have been published for 16 sites in the Pliocene equatorial Pacific, we use only the records (from nine sites in total) that have temporal coverage from the Pliocene to the Late Pleistocene (<0.5 Ma; Figures 1c and 1d, Table 1). Some sites lie outside of the regions commonly used to quantify El Niño states but are still affected by El Niño (e.g., ODP Site 1143). We include these sites in the reconstruction to increase the amount of variability captured by the limited field PCA and thereby improve the fidelity of the full field reconstruction. We required that the three youngest samples be less than or equal to 0.5 Ma in age to calculate the mean SST from 0 to 0.5 Ma, which we use to define the Pliocene SST anomalies. In cases where multiple SST records were present within the same 2° × 2° grid point, we used the record that had the longest duration if it had a comparable or higher temporal resolution than other sites in the same grid cell. The temporal resolution of the selected records ranges from 2–201 ka. Inter-site differences in sampling resolution are not problematic as the raw SST records (Figure 1d) are smoothed (Figure 1e) prior to PCA. The Mg/Ca and TEX_{86} records are located in both the west and east Pacific. By contrast, the one $U^{k'}_{37}$ record is located only in the east, and the assemblage-based records are only in the central and west Pacific.

The previously published SSTs were calculated with a variety of calibrations. For consistency, we recalculated SSTs from Mg/Ca ratios, $U^{k'}_{37}$, and TEX_{86} using one calibration for each proxy. The raw TEX_{86} values were converted to temperature using the calibration of Kim et al. (2010), which does not include the (sub)polar sites. The raw $U^{k'}_{37}$ values were converted to temperature using the global SST calibration of Müller et al. (1998). A new $U^{k'}_{37}$ temperature calibration using a Bayesian spline regression model (BAYSPLINE; Tierney & Tingley, 2018) has been proposed to address the temperature limit of $U^{k'}_{37}$ at the warm extreme ($U^{k'}_{37} > 0.8$). Although the temperatures reconstructed using BAYSPLINE do not have a maximum limit, the uncertainties at the warm end are large (up to 4.4 °C at 29.4 °C). Although $U^{k'}_{37}$ values at ODP Site 846 in the East Pacific are high (approaching 1), the full field SST reconstruction using BAYSPLINE with a prior standard deviation of 10 °C is no more than 0.5 °C higher than that derived from the Müller et al. (1998) calibration. Thus, the $U^{k'}_{37}$-derived SSTs calculated using these two calibrations are not distinguishable from one another within errors reported in each (Figure A1a).

The Mg/Ca-based SSTs were calculated using the *T. sacculifer* calibration of Dekens et al. (2002). This Mg/Ca-temperature calibration includes a dissolution correction based on water depth that is deemed appropriate for SST reconstruction since foraminifer dissolution is prevalent in the equatorial Pacific (e.g., Fehrenbacher & Martin, 2011; Mekik et al., 2007; Rongstad et al., 2017; Rosenthal et al., 2000; Thompson & Saito, 1974; Wycech et al., 2018). Although the degree of dissolution likely varied slightly through the study interval (Pälike et al., 2012), a temporal adjustment to ΔCO_3^{2-} has a negligible effect on the reconstructed SST trend (see Appendix A). More critically, our SST calculations include a correction for lower Mg/Ca ratios of Pliocene seawater (Mg/Ca_{sw}) provided by Zeebe and Tyrrell (2019). The correction for lower Mg/Ca_{sw} entailed multiplying the Mg/Ca-temperature pre-exponential constant by the ratio of paleo to modern Mg/Ca_{sw} (*sensu* Medina-Elizalde et al., 2008) where modern Mg/Ca_{sw} is 5.17 mol/mol (Rausch et al., 2012). Relative to the SSTs calculated with only the water depth correction, the Mg/Ca_{sw} adjustment increases SSTs by 1.5 °C on average with the adjustments being smallest for the youngest samples (~0.1 °C) and largest at ~5 Ma (2.5–2.6 °C; Figures A1b–A1d).

Each reconstructed SST datum reflects average conditions over several thousand years given the mean sampling interval at the study sites (1.81 cm) and the relatively slow Plio-Pleistocene sedimentation rates in the west (2.7–4.7 cm/kyr at Site 806) and east (2.1–3.8 cm/kyr at Site 850) Pacific. We smoothed the raw SST records using a local polynomial method, that is, a second order polynomial with 20% of the nearest data points (e.g., Loader, 1996) in order to obtain an SST value at any selected interval between 2 and 5 Ma (Figure 1e). The use of a larger local neighborhood (~70%) produced the same results as the smaller (20%), but the use of a smaller neighborhood is more appropriate for the long study period (5 million years) and sampling resolution. Specifically, 20% nearest neighbors equates to temporal smoothing windows of ~1 Ma for the $U^{k'}_{37}$, Mg/Ca, and foraminifer assemblage records and ~2 Ma for the TEX_{86} records.

Table 1
Equatorial Pacific SST Proxy Records

Site	Core	Latitude (°N)	Longitude (°E)	Water depth (m)	Youngest age (Ma)	Oldest age (Ma)	Average sampling resolution (ka)	Reference[a]
				$U^{k'}_{37}$ records				
1	ODP 846	−3.096	−90.818	3,296	0.005	5.090	2	Lawrence et al. (2006)
				Mg/Ca (*T. sacculifer*) records				
2	ODP 806	0.319	159.362	2,520	0.019	5.138	12	Wara et al. (2005)
3	ODP 847	0.193	−95.320	3,334	<0.01	5.393	21	Wara et al. (2005)
4	ODP 1237	−16.007	−76.378	3,212	0.01	5.000	77	Wara and Ravelo (2006)
				TEX86 records				
5	ODP 1241	5.843	−86.445	2,027	0.094	9.535	201	Seki et al. (2012)
6	ODP 850	1.297	−110.521	3,786	<0.01	11.88	150	Zhang et al. (2014)
7	ODP 1143	9.362	113.285	2,772	0.06	4.98	43	O'Brien et al. (2014)
				Foraminiferal assemblage records				
8	DSDP 200	12.837	−156.783	1,479	0.01	5.77	152	Wang (1994)
9	DSDP 289	−0.499	158.512	2,206	<0.15	6.25	114	Wang (1994)

[a]Raw data provided in Table S1.

We converted these SST records to anomalies by subtracting the 0–0.5 Ma average from each respective smoothed time series. The 0–0.5 Ma interval was selected as the base for anomaly calculations in order for the study to include more sites that would have otherwise been eliminated due to their pre-Holocene core tops (e.g., Sites 1241 and 806). Furthermore, the interval from 0 to 0.5 Ma includes multiple data points (3–288) from each record, which reduces the likelihood of aliasing. The inclusion of multiple glacial-interglacial cycles in the past 0.5 Ma introduces a cold bias into the base period 0–0.5 Ma. Because of this bias, we describe SST anomalies in reference to the "base period" (0–0.5 Ma), and not the modern, instrumental period, or the Holocene.

3. Reconstruction Method

We use the same PCA technique described in Gill, Rajagopalan, Molnar, and Marchitto (2016), and we briefly review the technique in the specific context of this study (Figure S1).

3.1. Principal Component Analysis (PCA)

PCA entails decomposition of multivariate space-time data into orthogonal space-time components, also referred to as modes, by eigen decomposition of the covariance matrix (see Von Storch & Zwiers, 2001). The spatial components are in the eigenvectors, also known as Empirical Orthogonal Functions (EOFs), while the temporal modes are the Principal Components (PCs). Projecting the PCs onto the eigenvectors transforms to the original data space. The components are ordered according to the percentage of total variance resolved such that the first few components capture most of the variance.

Application of PCA to paleoclimate SST reconstruction relies upon the spatial and temporal variability of the modern SSTs observed at each site. For this reason, we first performed a PCA on the full field of contemporary SSTs within the defined equatorial Pacific domain (16°N–16°S, 100°E–60°W) using the complete historical SST record (1854–2018) to maximize the amount of data input into the contemporary PCA. The first three modes were retained as they together explain 81% of the total variance in the historical record (Figure A2). Next, we performed a PCA on the contemporary SSTs in the limited field, that is, the spatial grid points with paleo-SST records. From this, the first two modes were retained as they together explain 83% of the total variance. Each of three PCs from the full field PCA are linearly regressed against the two PCs of the limited field—thereby fitting three linear regression models. For each selected time point, say 2 Ma, the paleo-SST anomaly at each site is multiplied by the contemporary limited field eigenvector matrix to obtain the limited field paleo PCs. Estimates of the three PCs of the full field are obtained using the linear regression

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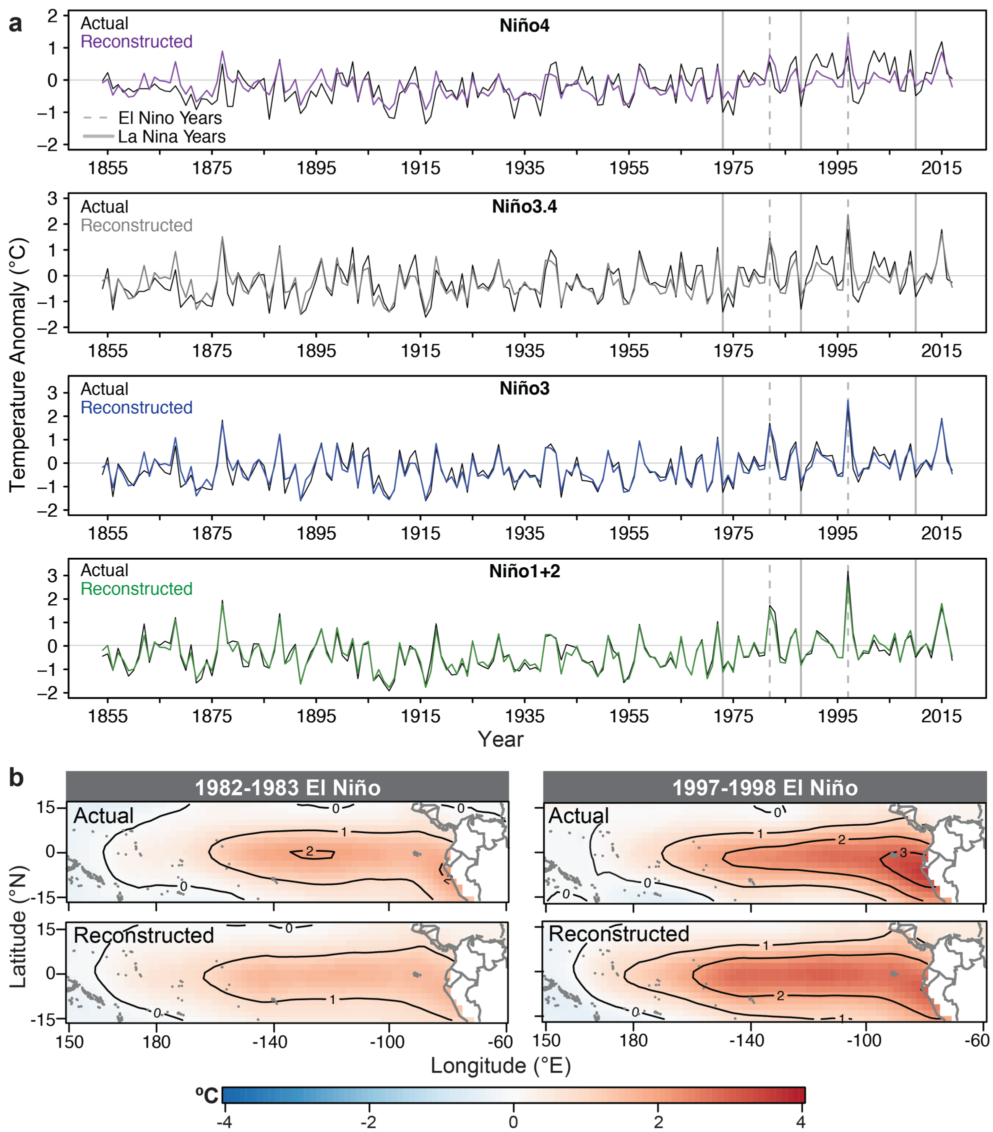

Figure 2. Model-data comparison of historical Niño Indices and El Niño events (a). Historical time series of observed (black lines) and reconstructed (colored lines) Niño 4, Niño 3.4, Niño 3, and Niño 1 + 2 temperature anomalies. Vertical gray lines mark years of the two strongest El Niño events (dashed lines; 1983–1984 and 1997–1998) and the two strongest La Niña years (solid lines; 1973–1974, 1988–1989, and 2010–2011). (b) Maps of actual and reconstructed SST anomalies for the 1982–1983 (left) and 1997–1998 (right) El Niño events.

models. The three PCs of the full field are projected back to the SST anomaly space by multiplication with the full field eigenvectors to reconstruct the full field of paleo-SST anomalies. We repeated this procedure at discrete time points (2, 3, 4, 4.3, and 5 Ma) to generate maps of equatorial Pacific SST anomalies. Reconstructions were also performed at small time steps (0.02 Ma) from 5 to 1 Ma to generate a time series of the Niño indices (Niño 4 = 5°N to 5°S and 160°E to 150°W, Niño 3.4 = 5°N to 5°S and 170°W to 120°W, Niño 3 = 5°N to 5°S and 150°W to 90°W, Niño 1 + 2 = 0° to 10°S and 90°W to 80°W) and the Western Trans-Niño Index (WTNI). WTNI is calculated by subtraction of WPAC (5°N to 5°S and 120°E to 160°E) from Niño 1 + 2 (Trenberth & Stepaniak, 2001). Niño indices are defined as the mean SST anomalies in each respective region and provide a quantitative means to monitor the state of ENSO in the equatorial Pacific. For example, development of modern El Niño events is apparent by increases in Niño 1 + 2 and WTNI due to positive SST anomalies in the eastern equatorial Pacific. PCA provides the means to calculate Niño indices for quantitative assessment of paleo-El Niño, which is otherwise not possible using the conventional comparison of temperature records from only two to three sites across the equator.

The uncertainty in the reconstruction was quantified by generating 500 ensembles of the full field PC estimates using the standard errors in the PCs from the regression models. Consequently, the ensembles of SST anomalies provide nominal estimates of uncertainty from the regression estimates of the PCs. While useful, this approach tends to underestimate the full standard error because it does not include the uncertainties in the regression model parameters and data. Future studies should consider Bayesian regression methods, which provide robust estimates of uncertainty by incorporating all sources of error (see Gelman & Hill, 2006).

3.2. Calibration of PCA Model

We performed calibration and validation tests to assess the estimates of past SSTs by reconstructing contemporary SSTs using the same limited field PCA approach (see Appendix A). We first compared actual and reconstructed historical time series of Niño indices (Figure 2a). Reconstructed SSTs agree best with the observed Niño indices for strong La Niña and El Niño events. Model-data mismatch is greatest for Niño 4 and Niño 3.4 due to the sparsity of limited field locations in these regions. Conversely, reconstructed SSTs best match the observed Niño 1 + 2 time series due to the numerous sites in the eastern equatorial Pacific. Although model-data mismatches exist where anomalies are not large, reconstructed SSTs capture the observed Niño indices for the two strongest El Niño events (1982–1983 and 1997–1998) and the three strongest La Niña events (1973–1974, 1988–1989, and 2010–2011) in the historical record (Figure 2a).

We then compared actual and reconstructed maps of SST anomalies for the aforementioned two strongest El Niño events (Figure 2b). For the 1982–1983 El Niño, reconstructed SSTs capture a maximum SST anomaly of 1.8 °C, which has the same spatial pattern of warming and is within 0.4 °C of the observed conditions (Figure 2b, left). Similarly, the reconstructed 1997–1998 SST anomalies show warming in both the eastern and central equatorial Pacific up to 3 °C, within 0.7 °C of those observed (Figure 2b, right). In summation, the numerous study sites in the region most affected by El Niño (from the eastern equatorial Pacific) enable accurate reconstruction of SSTs and bolster confidence in our reconstruction of paleo-El Niño-like SST distributions.

3.3. Assumptions

Applying the limited field approach to paleoclimate reconstructions requires several assumptions. First, we assume that the relationships among sites in the limited field are linearly related to relationships within the full field for the contemporary period. Second, we assume spatiotemporal variation in the contemporary SST record apply as far back at 5 Ma. This is an acceptable assumption given the warm eastern Pacific Pliocene SSTs and that modern ENSO teleconnections are evident among global Pliocene climate records (Fedorov et al., 2006; Lawrence et al., 2006; Molnar & Cane, 2002, 2007; Philander & Fedorov, 2003; Ravelo et al., 2006; Wara et al., 2005). Third, we consider the temperature-proxy relationships observed in laboratory culture or in modern sediments to be applicable back to 5 Ma. Relatedly, we assume that ontogenies of the biological carriers of the Mg/Ca, TEX_{86}, and $U^{k'}{}_{37}$ proxies did not change between the Pliocene and today. Fourth, we consider the proxies to record annual average SSTs throughout the equatorial Pacific. Although seasonality is low in the tropics, the assumption carries risk because the biological carriers of the proxies can sometimes prefer specific seasons or greater water depths (Harada et al., 2001; Leduc et al., 2010; Müller & Fischer, 2001; Ohkouchi et al., 1999; Rae et al., 2014). Finally, we acknowledge that the SST reconstruction reflects the mean state of the equatorial Pacific due to the time-averaging within single deep-sea samples, and therefore, our results do not elucidate interannual ENSO variability. A mean El Niño-like state may indicate increased ENSO amplitude and/or frequency or simply an increase in SST without a change in interannual variability.

4. Results—Pliocene Reconstructions

4.1. Limited Field SST Reconstruction

Prior to reconstructing the paleo full field of SST anomalies, we assess how well the method reconstructs each paleo-SST record (Figure 3). The goodness of fit between the reconstructions from our method and the smoothed paleo-SSTs were determined using the root mean square error (RMSE), noted in the upper right corner of each scatterplot. The reconstructions were performed at 0.5 Ma intervals from 5 to 0 Ma (sample size = 11). The first two eigenvector values are provided for each site and correspond to the circles mapped in Figure A3. These EOF values indicate the relative contribution of these data to the reconstruction of the full field. The RMSE values are typically within the error of the temperature reconstruction (1.2–2.2 °C, ±SE), reaching 1.5 °C for the poorest fits. The use of multiple proxies may explain some of the larger RMSE values. For example, foraminifer assemblages indicate less to no warming relative to nearby Mg/Ca-based records.

4.2. Equatorial Pacific SST Reconstruction

Figures 4a–4e show reconstructed SST anomaly maps for 5, 4, 4.3, 3, and 2 Ma. The reconstruction at 4.3 Ma is provided to illustrate the spatial distribution of SST anomalies during peak warming. These spatial snapshots are accompanied by a time series of the Niño indices, WTNI, and the absolute zonal SST difference generated by PCA analysis at 20 ka time steps (Figure 5a).

Warm SSTs prevail across the equatorial Pacific from 5 to 2 Ma with more extreme warming in the eastern and central than western equatorial Pacific. SST anomalies, up to 4.5 °C near the coast of South America, are present at 5 Ma with SST anomalies of 2 °C reaching as far as 165°E (Niño 4 = 1.6 °C; Figures 4e and 5b). The warming in the central and eastern Pacific increases to a maximum at 4.3 Ma (Niño 1 + 2 = 4.3 °C, Niño 3.4 = 3.5 °C; Figure 5a) with an inferred warming of 4.8 °C off the coast of Peru (Figure 4d). Meanwhile, SSTs in the western equatorial Pacific were within 1.5 °C of base period conditions through the study interval reaching a maximum at 5.0 Ma (WPAC = 0.7 °C) and a minimum at 4.0 Ma (WPAC = −1.1 °C). After 4.3 Ma, long-term cooling occurred across the equatorial Pacific with maximum anomalies in the easternmost Pacific of 4.3, 2.8, and 1.6 °C at 4, 3, and 2 Ma, respectively (Figures 4a–4c). The standard errors on the SST anomalies are relatively small for all temporal snapshots, 0.1–0.3 °C for most of the equatorial Pacific with maximum errors of 0.4 °C immediately off the coast of South America where anomalies are greatest (Figures 4f–4j).

The time series of Niño indices (Figure 5a) illustrate this temporal pattern of peak equatorial warming at 4.3 Ma (Niño 4 = 2.0 °C, Niño 1 + 2 = 4.3 °C) with subsequent gradual cooling toward base period conditions. The zonal SST difference across the Pliocene equatorial Pacific is of interest because warming in the east occurs when the Walker Circulation weakens and El Niño events occur today. Although warming in the Pliocene east Pacific alone is consistent with an El Niño-like SST pattern, Zhang et al. (2014) argue that the Pliocene equatorial Pacific had a modern west-east SST difference due to uniform warming everywhere. We reconstruct time series of the WTNI using anomalies and absolute temperatures ($\Delta SST_{West\text{-}East}$) to quantify the zonal SST difference from 5 to 1 Ma (Figure 5a). The positive WTNI in early Pliocene time indicates greater warmth in the east than west and a reduced zonal SST difference relative to the base period. We also calculate $\Delta SST_{West\text{-}East}$ by subtracting the WTNI from the 0–0.5 Ma average SST difference between the Niño 1 + 2 and WPAC regions (8.4 °C).

Our Pliocene results are consistent with an El Niño-like SST pattern given that the WTNI values are positive (Figure 5a), the Pliocene $\Delta SST_{West\text{-}East}$ values are lower than the 0–0.5 Ma average (Figure 5a), and the eastern equatorial cold tongue is diminished. The largest WTNI (4.4 °C) and lowest $\Delta SST_{West\text{-}East}$ (4.0 °C) occur at 4.14 Ma, the former of which is 1.2 °C larger than the WTNI observed during the 1997–1998 El Niño, and the inferred SST pattern resembles a strong El Niño (Figure 5b). The $\Delta SST_{West\text{-}East}$ minimum occurs ~200,000 years after peak warmth in the east due to cooling in the WPAC region from 4.3 to 4 Ma (Figures 4c–4d and 5a). The eastern equatorial Pacific gradually cools after 4 Ma, but the zonal SST difference does not reach base period conditions until ~1.5 Ma (Figure 5a).

5. Discussion

5.1. Proxy sensitivity to PCA Reconstruction

We investigated the sensitivity of the PCA reconstruction on the type of proxy included in the limited field data set (see supporting information). The first three iterations used a multiproxy approach in which either the $U^{k'}_{37}$, Mg/Ca, or TEX_{86} records were respectively removed and, whenever possible, replaced by a different proxy type from the same site. Results from these iterations indicate that removal of the $U^{k'}_{37}$ or TEX_{86}

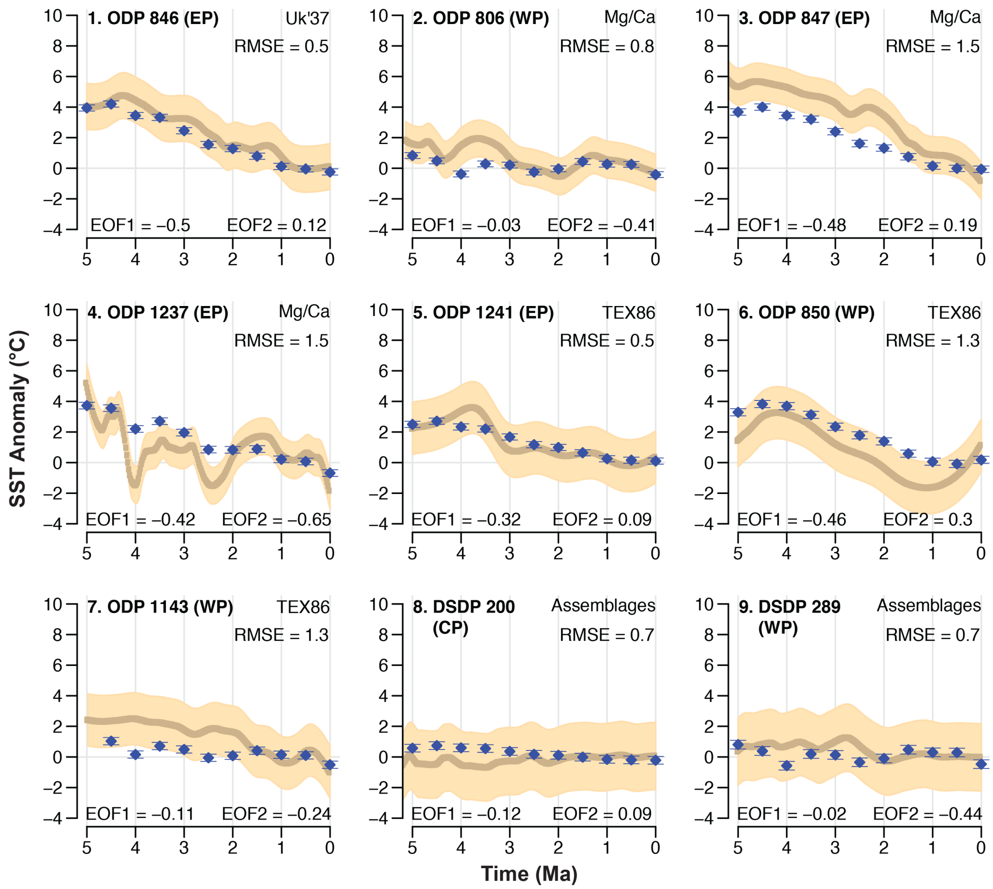

Figure 3. Scatterplots of each SST proxy record from the equatorial Pacific (yellow) with the reconstructed SST values for the grid point nearest each record (blue). Error of the proxy-temperature calibration is shaded in light yellow around each record: ±1.5 °C for $U^{k'}_{37}$ (Müller et al., 1998), ±1.2 °C for Mg/Ca (Anand et al., 2003; Dekens et al., 2002), ±1.7 °C for TEX_{86} (Kim et al., 2010), and ± 2.2 °C for foraminiferal assemblages (Wang, 1994). Standard errors from the reconstructed model are shown as blue whiskers. Site numbers in the upper left correspond to those noted in Table 1 and Figure 1. EP = East Pacific; CP = Central Pacific; WP = West Pacific. The root mean square error (RMSE) quantifies how closely the reconstructed SSTs match the proxy SSTs (°C). The first two eigenvector values are noted at each location (EOF1 and EOF2) since the first two modes of the limited field were used for the PCA-based reconstruction.

proxies changed the full field reconstruction by less than ~0.5 °C (Figures S2 and S4) while removal of the Mg/Ca proxy changed the full field reconstruction by less than ~1.5 °C (Figure S3).

An additional three iterations used a single proxy approach based on only $U^{k'}_{37}$, Mg/Ca, or TEX_{86}. The largest difference (2.1–3.3 °C) between these iterations (Figures S5–S7) and the original (Figure 4) occurred when the reconstruction was based only on TEX_{86} records (Figure S7). We further compared the minimum zonal SST difference (-WTNI; Table S2) and the west-east SST difference ($\Delta SST_{West\text{-}East}$) reconstructed by each iteration (Figure S8). The Mg/Ca-only and TEX_{86}-only iterations have the largest divergence from the original reconstruction because these iterations are based on only four SST records compared to the nine records used for the complete, multiproxy reconstruction (Table S2). By contrast, the minimum zonal SST differences from iterations 1–4 (−3.4 to −4.3 °C) are similar to that of the original reconstruction (−4.4 °C) and reproduce the trend and magnitude of the original $\Delta SST_{West\text{-}East}$ time series (Table S2, Figure S8). Agreement between the original reconstruction and the majority of the iterations indicates that (1) the inferred reduced zonal SST gradient is robust and (2) the reconstruction benefits from numerous SST records even when they are derived from multiple proxies. Some previous Pliocene reconstructions indicate the zonal SST difference across the equatorial Pacific was modern-like (e.g., Tierney et al., 2019; Zhang et al., 2014), which differs from the reconstruction presented herein. A potential explanation for such conflicting results is that the prior studies often use only one or two proxies and/or are focused on the mid-Pliocene warm period (3–3.3 Ma) when mean El Niño-like conditions were likely subsiding.

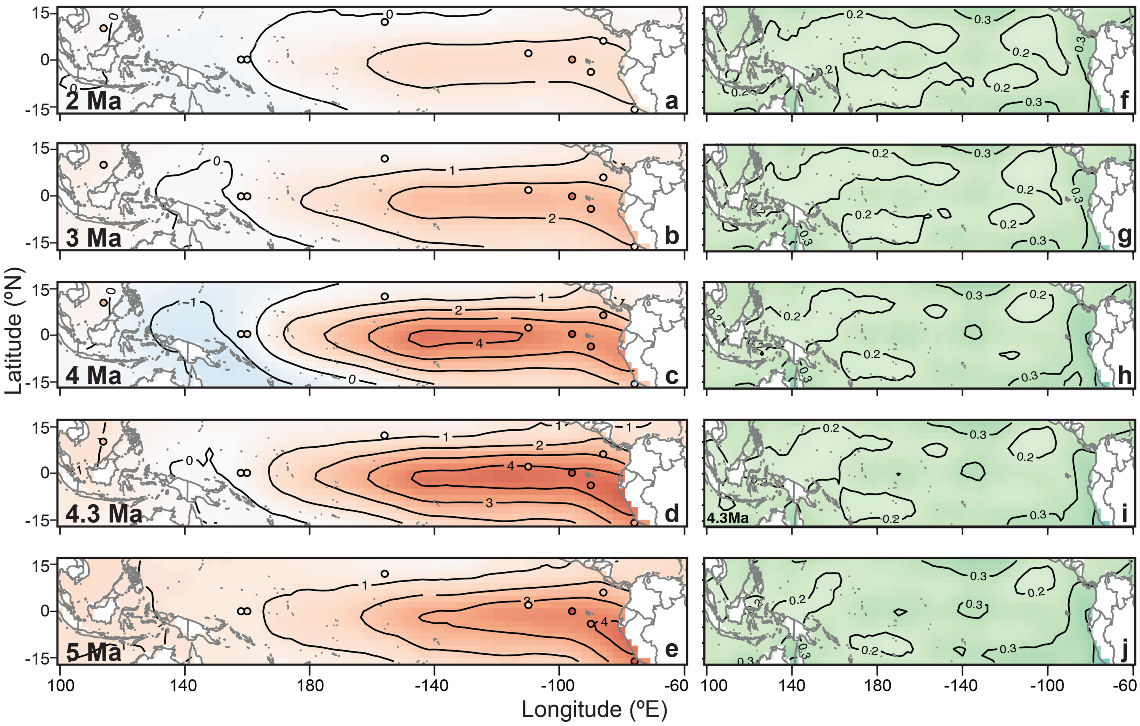

Figure 4. (a–e) Multiproxy reconstructed SST anomalies for 2, 3, 4, 4.3, and 5 Ma. Anomalies were defined relative to the 0–0.5 Ma average SST for each smoothed record. Circles note the proxy-based SST at each site using the same color bar. (f–j) Standard errors calculated from 500 ensembles of each PC. Ensembles for the first three PCs generated from the linear regression. Ensembles for each of the remaining PCs generated by bootstrapping values from the original PCs at each grid point.

5.2. Pliocene El Niño-like SST Distribution

Prior to this study, evidence for the Pliocene mean SST state resembling that during peak El Niño events was based on SST and thermocline reconstructions from a few strategically located sites across the equatorial Pacific (e.g., Ford et al., 2012; Lawrence et al., 2006; Ravelo et al., 2006; Seki et al., 2012; Wara et al., 2005). We provide a broader reconstruction of SST anomalies across the region as well as quantifying Niño indices and the zonal SST difference. The results presented herein support mean early Pliocene El Niño-like SSTs, characterized by a warm central and eastern equatorial Pacific and a reduced zonal SST difference (Figures 4a–4e and 5a; Dekens et al., 2008; Groeneveld et al., 2006; Lawrence et al., 2006; Ravelo et al., 2006, 2014; Seki et al., 2012; Steph et al., 2006; Wara et al., 2005). The magnitude and spatial pattern of warming across the equatorial Pacific during the early Pliocene was more extreme than the strongest El Niño event in the historical record (1997–1998; Figure 2b). This finding supports the inference that the 1997–1998 El Niño is the best modern analog for Pliocene conditions (Molnar & Cane, 2007).

Previous studies suggest El Niño conditions terminated ~4 Ma due to the hypothesized closure of the Central American and/or Indonesian Seaways (Cannariato & Ravelo, 1997; Chaisson & Ravelo, 2000; Steph et al., 2010; Zhang et al., 2012). By contrast, our reconstructions indicate slow, long-term deterioration of El Niño-like conditions after 4.1 Ma (see WTNI and $\Delta SST_{West\text{-}East}$ time series in Figure 5 a) such that a perturbation to the ocean-climate system by a single tectonic event cannot explain the shift toward modern conditions.

Modern El Niño events impact global precipitation and temperature patterns (Ropelewski & Halpert, 1996). Some general circulation models with a warm eastern equatorial Pacific do not yield major large-scale anomalies like those during El Niño (Bonham et al., 2009; Haywood et al., 2007), but others are able to simulate such teleconnections (e.g., Barreiro et al., 2005). Although high SST anomalies in the east are a salient feature of the Pliocene equatorial Pacific, our study does not elucidate how this El Niño-like SST pattern affects global temperatures.

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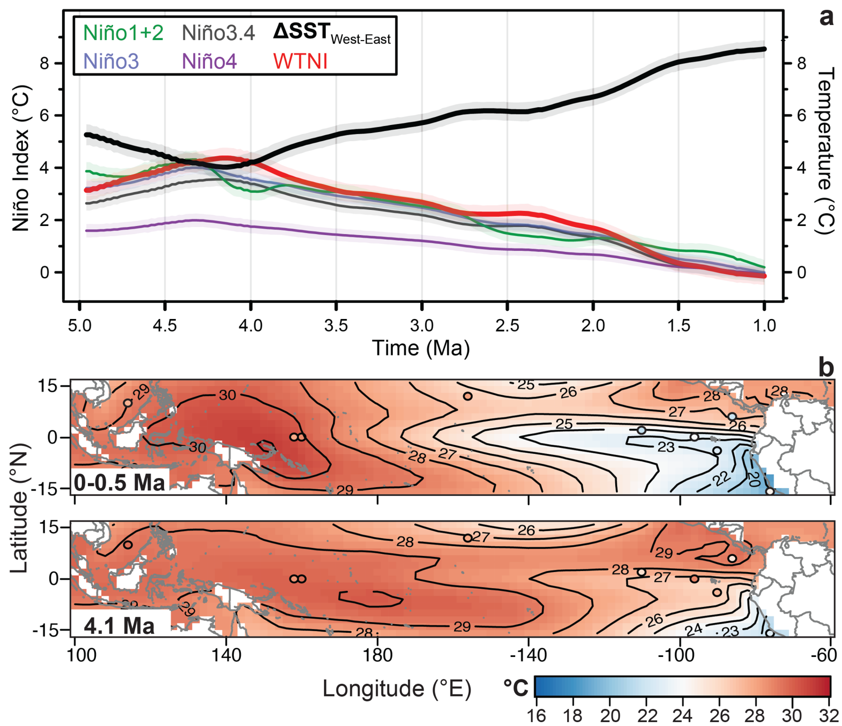

Figure 5. (a) Plio-Pleistocene time series of Niño indices (temperature anomalies, left axis), the WTNI [(Niño 1 + 2) – WPAC] SST anomaly difference, and the absolute zonal SST difference ($\Delta SST_{West\text{-}East}$; right axis) calculated relative to the 0–0.5 Ma average value (8.4 °C; see section 4.2). The time series were calculated from PCA reconstructions at 0.02 Ma intervals. Shading around each time series is one standard error propagated from PCA reconstruction. (b) Maps of the average SSTs from 0 to 0.5 Ma and the reconstructed SSTs at the $\Delta SST_{West\text{-}East}$ minima (4.1 Ma). Colors in circles show the proxy-based SST at each site and use the same color scale as in the maps.

5.3. Constraints on Pliocene Indian Summer Monsoon Rainfall

Since the Pliocene is considered to be an analog for future climate conditions, reconstructing Pliocene Indian Summer Monsoon bears on relative rainfall changes expected in the region by the end of the 21st century. Warming in the central equatorial Pacific during modern El Niño events weakens Indian Summer Monsoon rainfall via atmospheric teleconnection (e.g., Krishna-Kumar et al., 2006). We pair this modern observation with our Pliocene equatorial Pacific SST reconstruction to estimate the strength of Pliocene monsoon. Rainfall anomalies (Pliocene-base period) are calculated using the paleo-Niño 4 time series (Figure 5a) and the modern correlation between Niño 4 and scaled monsoon precipitation (Indian Institute of Tropical Meteorology; $ISM_{precip,scaled} = -1.91 \times \text{Niño4} + 0.11$, $R^2 = 0.25$). The Niño 4 region is warmer than the base period from 5 to 1 Ma, which produces negative rainfall anomalies, that is, drier conditions throughout the study interval (Figure 6a). Our most extreme estimate suggests the monsoon could have been ~37% weaker than today during the interval with the most intense equatorial Pacific warming (4.3 Ma).

Evidence for weaker Indian Summer Monsoon during the Pliocene relative to today is spatially pervasive in both marine and continental realms (Figure 6b) and consistent with Pliocene climate model results (e.g., Brierley & Fedorov, 2010; Fedorov et al., 2013). Relative to modern, early Pliocene sediments from the Bay of Bengal have lower accumulation rates, reduced concentrations of run-off proxies (Mn, Fe, K/Al), higher calcium carbonate content, smaller particle sizes, more weathered clays, and lower abundances of a benthic foraminifer that prefers high productivity waters (Burbank et al., 1993; Clift et al., 2008; Gourlan et al., 2008; Gupta & Thomas, 2003; Prell & Kutzbach, 1997). Similarly, the Indus Fan and Yuanmou Basin have lower sedimentation rates (Chang et al., 2010; Clift et al., 2008), and the $\delta^{18}O$ values of calcite cements within the Siwalik Sandstone at Surai Khola suggest more arid conditions from 4 to 2 Ma (Sanyal et al., 2005). The pervasive evidence for higher residence times of sediments within the floodplain, drier conditions, and less Pliocene continental weathering relative to present-day is consistent with weaker monsoon rainfall, particularly around 4.3 Ma.

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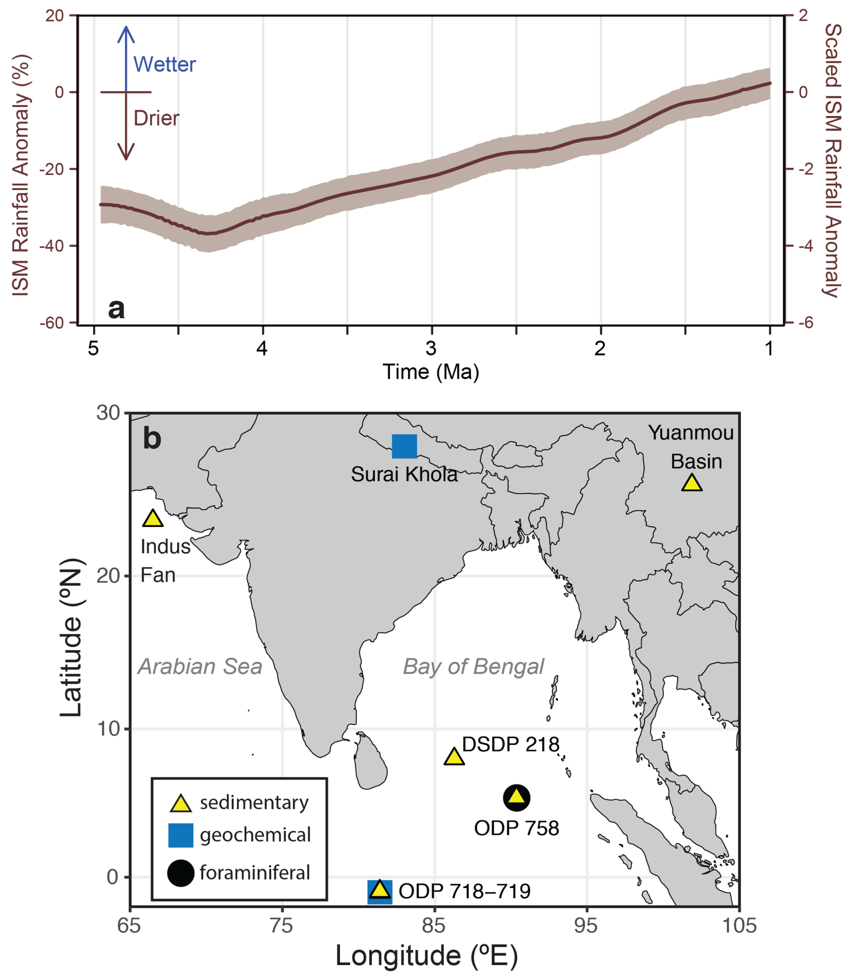

Figure 6. Reconstruction of Indian Summer Monsoon strength and summary of previously published paleo-monsoon observations. (a) Time series of reconstructed rainfall anomalies (percent on left axis, scaled on right axis; see section 5.3 for reconstruction details). One standard error propagated from SST reconstruction is shown as the brown shaded area around the anomaly record. (b) Summary of locations with sedimentary, geochemical, or foraminiferal proxy records that reflect hydrologic conditions, all of which indicate a weaker monsoon during the early Pliocene (Chang et al., 2010; Clift, 2006; Clift et al., 2008; Farrell & Janecek, 1991; Gartner, 1989; Gupta & Thomas, 2003; Hovan & Rea, 1992; Rea, 1992; Sanyal et al., 2005).

6. Conclusion

We use a multiproxy reduced-dimension methodology on previously published equatorial Pacific SST records spanning 5–0 Ma to reconstruct spatial and temporal images of the Pliocene mean El Niño-like state. We find that the Pliocene equatorial zonal SST difference across the Pacific was reduced by ~4.4 °C relative to the comparison period (0–0.5 Ma) due to extreme warming of up to 4.8 °C in the east and minimal warming in the west. The warming peaked at 4.3 Ma and gradually declined towards the modern (La Niña-like) state. The added value of our approach is the production of high spatial resolution maps (2° × 2°) of SST anomalies, which allows for the calculation of Niño indices and estimates of precipitation/temperature anomalies in distal regions teleconnected to El Niño. We provide an estimate of the strength of Pliocene Indian Summer Monsoon based on the paleo-Niño 4 reconstruction. Our results suggest the Pliocene monsoon may have been ~16–37% weaker than the 0–0.5 Ma average, which is consistent with continental and marine geological evidence from the region. In summary, our results support the argument for the Pliocene mean El Niño-like state and supply quantitative estimates on the strength of paleo-ISM. We further conclude that our reconstruction of a reduced zonal SST gradient is more robust than previous studies due to the multiproxy approach that improves spatial coverage of paleo-SST data across the equatorial Pacific.

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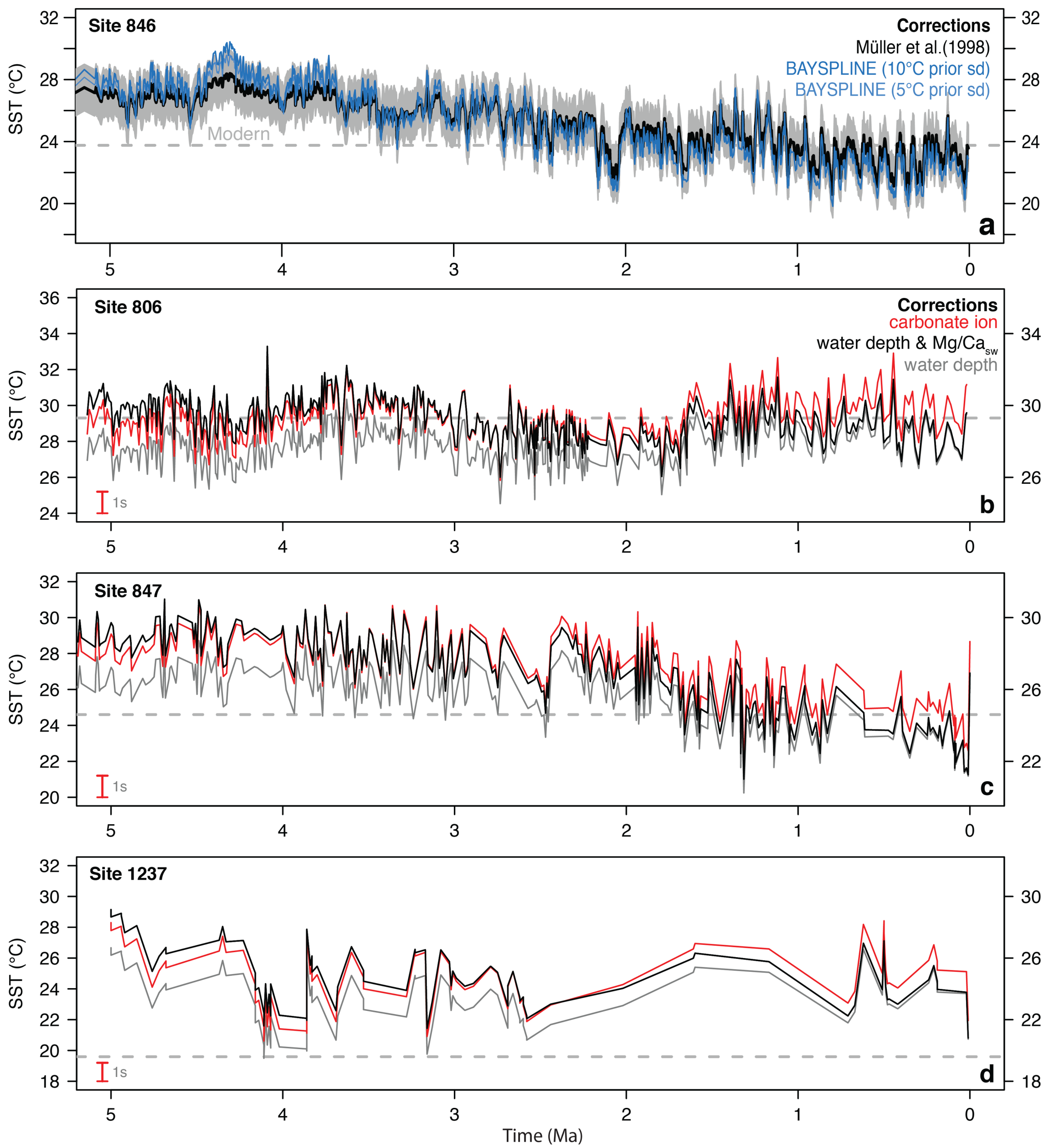

Figure A1. Comparison of Plio-Pleistocene SST records reconstructed using different calibrations on (a) one $U^{k'}_{37}$ record from east Pacific ODP Site 846, and Mg/Ca records from (b) west Pacific ODP Site 806 and (c–d) east Pacific ODP Sites 847 and 1237, respectively. Dashed gray horizontal line marks modern SST at each site. (a) SSTs reconstructed using Müller et al. (1998) (black line) and BAYSPLINE calculated with prior standard deviations of 10 (dark blue line) and 5 °C (light blue line). Gray shading notes ±1.5 °C error on the black line (Müller et al., 1998). (b–d) SSTs calculated using the Dekens et al. (2002) calibration and corrections for dissolution based on water depth (gray lines) or the modern bottom water ΔCO_3^{2-} value (red lines). Black line is the SST record used for this study using the depth-based dissolution correction and a paleo-Mg/Ca$_{sw}$ record (Zeebe & Tyrrell, 2019). Red error bars note Mg/Ca calibration error (±1.2 °C SE; Anand et al., 2003; Dekens et al., 2002).

Appendix A.: Detailed Research Methods

This appendix provides further details on the SST reconstruction from $U^{k'}_{37}$ and Mg/Ca measurements, PCA output, and the calibration and validation of the model.

A.1. SST Reconstruction from $U^{k'}_{37}$ and Mg/Ca Ratios

We compared $U^{k'}_{37}$-based SSTs reconstructed using the linear calibration of Müller et al. (1998) (M98 hereafter) and BAYSPLINE (Tierney & Tingley, 2018; Figure A1a). At 4.3 Ma, SSTs reconstructed with both calibrations reach maxima of 28.4 °C using M98 and 30.4 °C using BAYSPLINE. The BAYSPLINE-derived SSTs,

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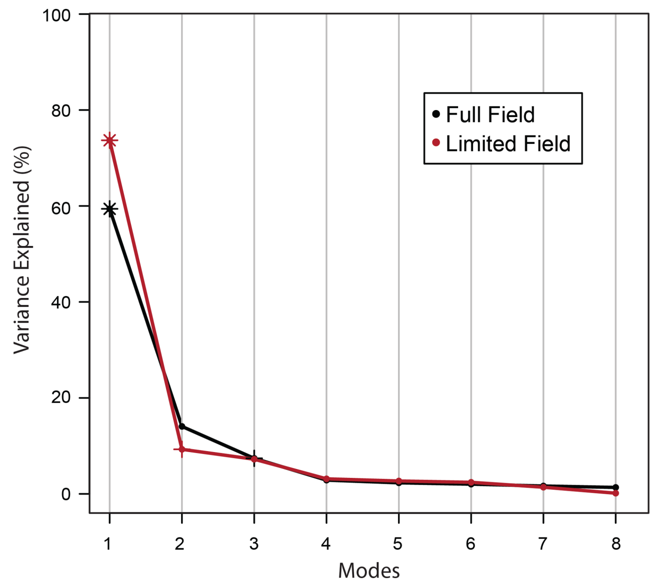

Figure A2. Eigenvalue spectra for the full SST field (black) and limited SST field (red). Asterisks note the variance explained by the first mode of each field. Plus signs mark the "knees," the points just before the noise floor (5%).

which applied a conservative prior standard deviation of 10 °C, are on average 0.6 °C less than those calculated with M98 after 2 Ma but are on average 0.8 °C higher than those calculated with M98 from 4 to 5 Ma. The difference between the linear- and BAYSPLINE-calculated SSTs, however, is within one standard error of either calibration (±1.5 °C from M98; 1.4–4.4 °C from BAYSPLINE).

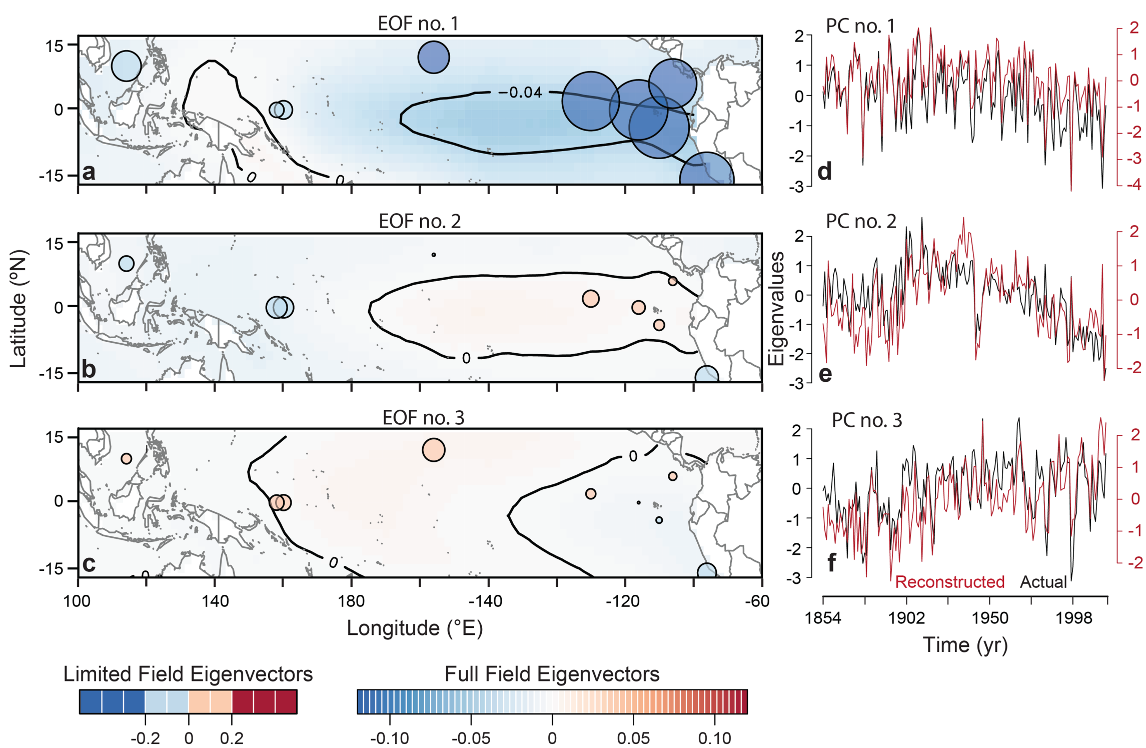

Figure A3. (a–f) EOFs (shaded map) and normalized PCs (black time series) of the two leading modes of the PCA performed on the full field of contemporary equatorial Pacific SSTs. Limited SST field EOFs (circles, areas scaled to eigenvalues) and normalized PCs (red time series). All EOFs are multiplied by their respective eigenvalue (proportion of variance explained by that mode) to show relative strengths through subsequent modes. The first three eigenvalues are $\lambda_1 = 0.594$, $\lambda_2 = 0.141$, and $\lambda_3 = 0.074$ for the full field PCA and $\lambda_1^{\dagger} = 0.737$ and $\lambda_2^{\dagger} = 0.093$ for the limited field PCA.

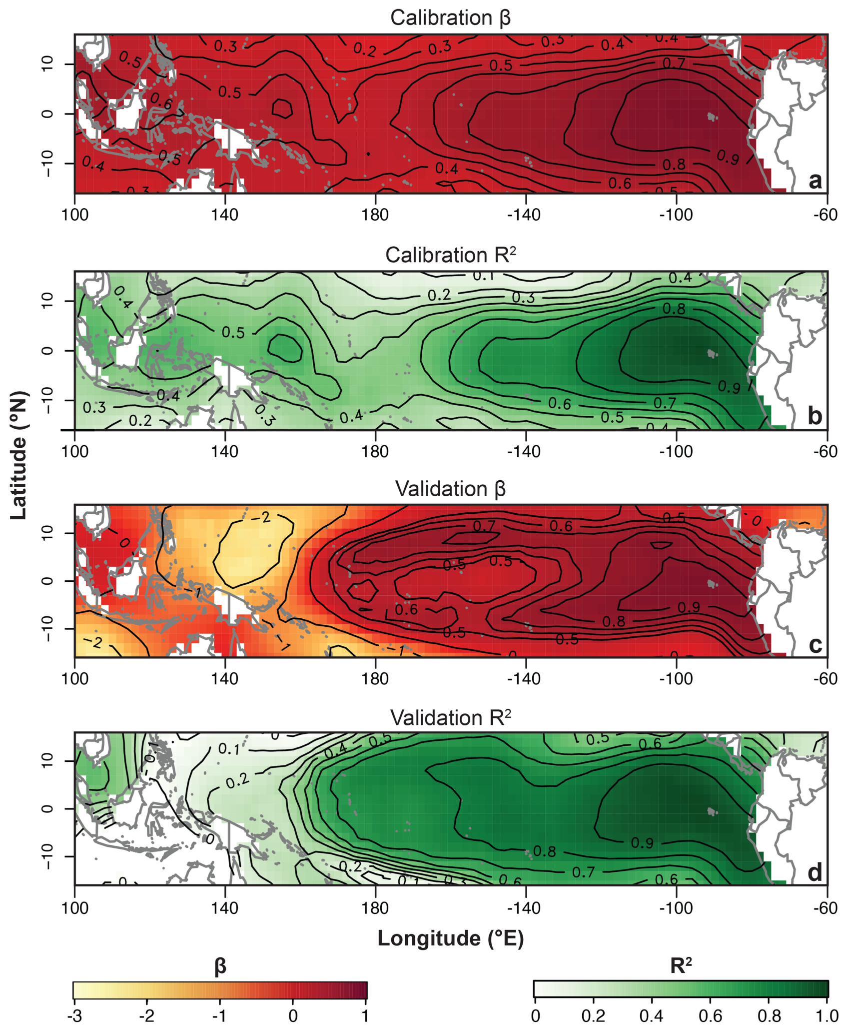

Figure A4. (a–b) Model calibration statistics for the PCA-based SST model (shading and black contours) showing the skill of the models in reconstructing the contemporary data set. The β statistic represents the resolved variance captured by the reconstructed contemporary data. The R^2 equals the square of the correlation between the observed and reconstructed contemporary data. (c–d) Model validation was performed by training the model on 1980–2013 data and using that model to validate SSTs from the period prior (1854–1979). The β and R^2 statistics again quantify model skill.

Our SST reconstruction from foraminiferal Mg/Ca ratios entails two adjustments, one for dissolution and one for the history of ratios of Mg/Ca in seawater, Mg/Ca_{sw} (see section 2.2, Figures A1b–A1d). We compare our Mg/Ca-based SST time series to those reconstructed with the two *T. sacculifer* calibrations from Dekens et al. (2002) that correct for dissolution either based on water depth or the modern ΔCO_3^{2-} value (gray and red lines, respectively, in Figures A1b–A1d). We calculated the $\Delta CO_3^{2-}{}_{modern}$ at sites 806, 847, and 1237 (−11.5, −25.6, and −20.9 μmol/kg, respectively) using bottom water conditions and the program CO2SYS v.2.1 (Lewis & Wallace, 1998) with the default dissociation constants (Mehrbach et al., 1973), as refit by Dickson and Millero (1987). We obtained bottom water temperature, pressure, dissolved phosphate, and dissolved silica concentrations from the World Ocean Database 2013 (Boyer et al., 2013). Total alkalinity and total dissolved inorganic carbon values were obtained from GLODAP (National Center for Atmospheric Research Staff, 2014). The degree of dissolution may have varied through the study interval, and we investigated these effects by adjusting the ΔCO_3^{2-} values input into the Dekens et al. (2002) calibration using the published paleo-CCD time series (Pälike et al., 2012) and the modern equatorial Pacific ΔCO_3^{2-} depth relationship (ΔCO_3^{2-} decreases by 0.0136 μmol/kg per 1 m depth increase for water depths >2,000 m). This temporal adjustment to

ΔCO_3^{2-} had a minimal effect on the reconstructed SST (<0.1 °C). The SSTs calculated with the modern ΔCO_3^{2-} value are ~1.5° higher on average, with recent interglacials seemingly too warm, compared to those adjusted based on water depth, so we favor the latter.

There is robust evidence that Pliocene Mg/Ca_{sw} was lower than modern (Coggon et al., 2010; Fantle & DePaolo, 2006; Higgins & Schrag, 2012; Horita et al., 2002; Lowenstein et al., 2001; Zeebe & Tyrrell, 2019; Zimmerman, 2000), and a Mg/Ca_{sw} correction has been shown to reconstruct warmer-than-modern West Pacific SSTs (Medina-Elizalde et al., 2008; O'Brien et al., 2014) that are reasonable considering CO_2 forcing (Ford & Ravelo, 2018). At west Pacific Site 806, the average SST reconstructed with the Mg/Ca_{sw} correction are 0.5 °C colder than the modern SST (29.3 °C, 1981–2010 mean) from 3–0 Ma, but 0.5 °C higher than modern from 5 to 3 Ma (Figure A1b). By contrast, the SSTs reconstructed with only the depth-based dissolution correction at Site 806 are 1.6 °C colder than modern on average and do not have a temporal trend from 5 to 0 Ma.

A.2. Principal Component Analysis (PCA) SST Reconstruction

Pliocene SST reconstruction via PCA entails use of the first few PCs of the limited field to model the first few PCs of the full field. The eigenvalues (λ) for each PC (Figure A2) were used to define the cutoff of PCs to include in the model. Although defining such a cutoff is arbitrary, it is important to include the appropriate number of PCs to maximize the amount of total variance captured while minimizing the amount of noise. We define the cutoff based on “knees” of the eigenvalue spectra, the smallest eigenvalues above the noise floor ($\lambda > 0.05$; represented by the plus signs in Figure A2).

We model the first three modes of the full field ($\lambda_1 = 0.594$, $\lambda_2 = 0.141$, and $\lambda_3 = 0.074$) using the first two modes of the limited field (${\lambda_1}^{\dagger} = 0.737$ and ${\lambda_2}^{\dagger} = 0.093$). The limited field captures 83% of the total variance, but the spatial distribution of the eigenvector magnitude is not uniform across the region (Figures A3a–A3c). Specifically, EOF1 weightings are highest in the east equatorial Pacific. This information is useful for future drilling projects that aim to assess paleo-SST variability within the equatorial Pacific. We also assessed the effectiveness of the approach by comparing the actual (observed) and reconstructed eigenvalues for the first three PCs (Figures A3d–A3f). The model-data eigenvalue agreement bolsters confidence in the Pliocene SST reconstruction using this method.

A.3. Model Calibration and Validation using β and R^2 Statistics

We use two criteria (β and R^2 statistics) to assess the ability of the model to reconstruct the contemporary full field SSTs from the limited field. The resolved variance statistic (β) is given by

$$\beta = 1 - \frac{\sum (y - \hat{y})^2}{\sum y^2}, \tag{A1}$$

where y is the contemporary data and $\hat{y}$ is the reconstructed data for the full period (1854–2017). The β statistic is computed at each grid point within the equatorial Pacific domain (Figure A4a). A β statistic equal to 1 indicates a perfect fit, and −1 indicates two random series. The β values range from 0.2 to greater than 0.9 across the reconstruction domain. The lowest β values occur in the western equatorial Pacific, where there are few/no limited field sites. Conversely, the highest β values (up to 0.98) occur in the eastern equatorial Pacific with numerous limited field sites.

The squared correlation statistic (R^2) indicates the strength of correlation between the observed and reconstructed SSTs at each grid point (Figure A4b). Similar to the calibration β map, the region with fewer limited field sites, the western equatorial Pacific, has lower R^2 values (0.2–0.5) than the region with numerous limited field sites, the eastern equatorial Pacific ($R^2 = 0.70$–0.98).

For model validation, we trained the PCA using only recent SSTs (1980–2013). We then reconstructed the full field SSTs for the earlier contemporary period (1854–1979) using the trained PCA model and computed the β and R^2 statistics to assess the fitting and correlation, respectively, between the observed and reconstructed SSTs (1854–1979). The validation β and R^2 values are lower than the calibration statistics in the western equatorial Pacific, again due to few limited field sites (Figures A4c–A4d), but validation statistics for the eastern and central regions remain high ($\beta = 0.50$–0.97 and $R^2 = 0.5$–0.99).

Acknowledgments

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