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Key Points:

- A 5 Myr record of subsurface temperatures from the western Pacific warm pool is presented
- Equatorial thermocline was warm, deep, and weakly tilted during the Pliocene El Padre mean state
- Thermocline cooling and/or shoaling initiated feedbacks vital to modern tropical dynamics

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The evolution of the equatorial thermocline and the early Pliocene *El Padre* mean state

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Abstract The tropical Pacific thermocline strength, depth, and tilt are critical to tropical mean state and variability. During the early Pliocene (~3.5 to 4.5 Ma), the Eastern Equatorial Pacific (EEP) thermocline was deeper and the cold tongue was warmer than today, which resulted in a mean state with a reduced zonal sea surface temperature gradient or *El Padre*. However, it is unclear whether the deep thermocline was a local feature of the EEP or a basin-wide condition with global implications. Our measurements of Mg/Ca of *Globorotalia tumida* in a western equatorial Pacific site indicate Pliocene subsurface temperatures warmer than today; thus, *El Padre* included a basin-wide thermocline that was relatively warm, deep, and weakly tilted. At ~4 Ma, thermocline steepening was coupled to cooling of the cold tongue. Since ~4 Ma, the basin-wide thermocline cooled/shoaled gradually, with implications for thermocline feedbacks in tropical dynamics and the interpretation of TEX_{86}-derived temperatures.

1. Introduction

The equatorial thermocline is key in determining the mean state (average oceanic and atmospheric conditions) and variability of the tropical Pacific climate [*Fiedler and Talley*, 2006; *Wang and Fiedler*, 2006]. Perturbations in thermocline depth and tilt contribute to El Niño–Southern Oscillation, which is the largest source of global interannual variability and has far-field, sometimes devastating, impacts. In the tropical Pacific, the thermocline is characterized by a strong east-west tilt (Figure 1). Trade winds force warm water to the west, creating the warm pool in the Western Equatorial Pacific (WEP) with a deep thermocline. The Eastern Equatorial Pacific (EEP) has a shallow thermocline and sea surface temperatures (SSTs) are spatially variable due to prevailing wind patterns and upwelling. In the Eastern Pacific Warm Pool (EPWP), located just north of the equator, weak winds prevent strong entrainment at the base of the surface mixed layer such that the surface is warm and stratified. However, in the cold tongue, which is the most prominent feature of the EEP, wind-driven upwelling brings cold water to the surface, tightly coupling SSTs to the shallow thermocline. The equatorial thermocline depth is also important to the global heat budget in the following ways: (1) a deep thermocline in the WEP controls the spatial extent of the warm pool and atmospheric latent heat transport [*Tian et al.,* 2001] and (2) the shallow thermocline in the EEP allows for cold water to upwell in the cold tongue which absorbs a significant amount of heat [*Boccaletti et al.,* 2004]. Latent and sensible heat from the tropics is then redistributed to high latitudes.

The early Pliocene warm period (~3.5 to 4.5 Ma) is the most recent period of sustained warmth and provides an opportunity to study the role of the equatorial thermocline in determining tropical Pacific climate over long timescales. Global temperatures are estimated to have been 2–3°C warmer than present [*Dowsett et al.,* 2012; *Lunt et al.,* 2012], atmospheric CO_2 concentration was similar to or slightly higher than modern anthropogenic levels [*Pagani et al.,* 2010; *Seki et al.,* 2010] and the Pacific zonal temperature gradient was reduced but not absent [*Ravelo et al.,* 2014]. This reduced zonal temperature gradient is similar to a modern El Niño event [*Wara et al.,* 2005] but because the mechanisms that drive El Niño–Southern Oscillation are different than those that determine the tropical Pacific mean state, we choose to call this early Pliocene warm period *El Padre* [*Ravelo et al.,* 2014].

During the early Pliocene, subsurface temperatures throughout the EEP were warmer than today, suggesting that the tropical thermocline was relatively deep and/or warm, at least locally [*Steph et al.,* 2006, 2010; *Ford*

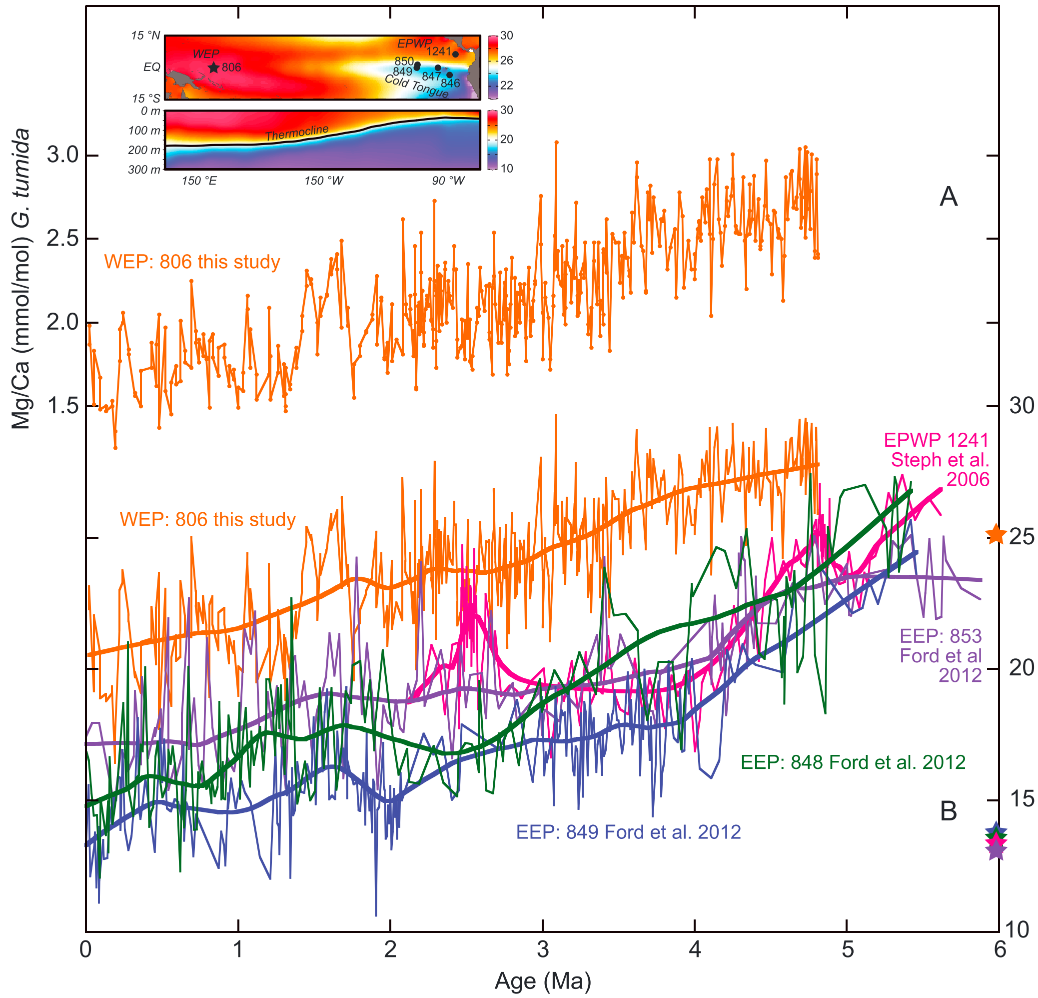

Figure 1. (Inset) SST map *Locarnini et al.* [2010] with site locations, cross section with 20°C isotherm (approximate thermocline position) ODV, *Schlitzer* [2015]. (a) *G. tumida* Mg/Ca record at WEP Site 806 (this study), (b) converted to subsurface temperature and previously published records [*Steph et al.,* 2006; *Ford et al.,* 2012]. Thick lines are locally weighted (20%) least squares smoothing. Stars indicate modern subsurface temperature at 125 m.

et al., 2012]. These records may also reflect conditions local to the EEP, such as an open Panama Seaway [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012; *Zhang et al.,* 2012] and/or changes in Pacific basin-wide thermocline tilt [*Chaisson*, 1995; *Chaisson and Ravelo*, 2000]. Additionally, there are some detailed differences in EEP subsurface temperature records that may be related to changes in regional wind patterns and strength [*Hovan*, 1995; *Ford et al.,* 2012]. To investigate the possibility that there were Pacific-wide changes in the tropical thermocline depth and tilt over the last 5 million years, we generated a low-resolution subsurface temperature record using the Mg/Ca values of *Globorotalia tumida* from the WEP warm pool. By comparing our new record to previous published records from the EEP, we show that the tropical thermocline was warm, deep, and had a weak tilt during the *El Padre* mean state and that cooling/shoaling of the thermocline occurred gradually over the last 4 myrs, playing a critical role in dynamic feedbacks important to modern climate.

2. Methods and Approach

2.1. Site Location and Age Model

We used Ocean Drilling Prorgam (ODP) Site 806 (0°N, 159°E, 2520 m water depth, Figure 1) to monitor the WEP warm pool subsurface state. Today, the WEP is characterized by warm SSTs (>27°C) and a deep thermocline (~150 m) [*Wang et al.,* 2000]. The age model is based on a high-resolution benthic isotope (0–4 Ma [*Bickert et al.,* 1993]) and bulk density record (>4 Ma [*Mayer et al.,* 1993]).

2.2. Foraminiferal Minor Element Analysis

We analyzed planktonic foraminifera *Globorotalia tumida* for minor element ratios to reconstruct a low-resolution (average sampling interval ~18,000 years) subsurface temperature record (Figure 1a). This species is ideal because in the modern ocean, *G. tumida* calcifies at the base of the photic zone [*Ravelo and Shackleton*, 1995] at a relatively constant depth (100–150 m) in a variety of hydrographic settings, irrespective of thermocline depth [*Ravelo and Fairbanks*, 1992; *Rincón-Martínez et al.,* 2011].

Samples were washed, dried, and picked for *G. tumida* from the 355–425 μm size fraction. Approximately 10 to 25 specimens were crushed, sonicated in Milli-Q and methanol, washed with reductive and oxidative reagents, and transferred to acid-cleaned vials [*Martin and Lea*, 2002] for minor elemental analysis. Samples were analyzed via Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) [*Wara et al.,* 2003]. Long-term reproducibility of a liquid consistency standard was 3.318 ± 0.030 mmol/mol ($1\sigma, n = 401$) and of a bulk foraminifera standard was 3.737 ± 0.181 mmol/mol ($1\sigma, n = 103$).

2.3. Temperature Gradient Estimates

Surface-to-subsurface vertical ($\Delta T_{\text{surface-subsurface}}$) and west-to-east zonal temperature gradients are useful in determining upper ocean coupling and the relative strength of climate dynamics (e.g., upwelling, Walker Circulation). We calculated temperature gradients using data generated in this study and previously published temperature estimates (Figure 2) [*McClymont and Rosell-Mele*, 2005; *Wara et al.,* 2005; *Lawrence et al.,* 2006; *Ford et al.,* 2012; *Zhang et al.,* 2014]. All data were converted to temperature using a uniform calibration for each proxy: Mg/Ca$_{G.\ tumida}$ was converted to temperature using the *G. tumida*-specific calibration of *Mohtadi et al.* [2011] (Figures 1 and 2), Mg/Ca$_{G.\ sacculifer}$ was converted to temperature using the $\Delta CO_3{}^{2-}$ corrected *G. sacculifer*-specific calibration of *Dekens et al.* [2002] (806: 10.5 μmol/Kg, 847: −10.3 μmol/Kg, 1241: 5.8 μmol/Kg), $U^{K'}_{37}$ was converted to temperature using *Müller et al.* [1998] and TEX_{86} was converted to temperature using *Kim et al.* [2010] (Figure 2). Because these records have different temporal resolution, all records were resampled with a 0.25 Ma Gaussian weighted running mean and then $\Delta T_{\text{surface-subsurface}}$ and zonal temperature gradients were calculated using the resampled data (Figure 3).

Though many subsurface records exist for the EEP, the Site 849 Mg/Ca$_{G.\ tumida}$ record was used to calculate $\Delta T_{\text{surface-subsurface}}$ because it is representative of EEP conditions (Figure 1b) and has been on or very near the equator for the last 5 Myr. As no Pliocene SST record exists for Site 849, the Site 847 Mg/Ca$_{G.\ sacculifer}$ and Site 846 $U^{K'}_{37}$ records were used to monitor cold tongue SST conditions [*Wara et al.,* 2005; *Lawrence et al.,* 2006]. The available mid-Pleistocene $U^{K'}_{37}$ record from Site 849 [*McClymont and Rosell-Mele,* 2005] shows good agreement with Site 847, probably due to the fact they are both on the equator (Figure 3). Although many SST and subsurface temperature records exist from the EEP, we find similar $\Delta T_{\text{surface-subsurface}}$ and west-to-east zonal temperature gradient relationships; thus, the results described below to not depend on choice of record.

3. Results and Discussion

3.1. Potential Biases in Mg/Ca-Derived Temperatures

Some authors have suggested long-term changes in the Mg/Ca of seawater (Mg/Ca$_{\text{seawater}}$) may bias Mg/Ca-based proxies toward lower temperature reconstructions for the middle to early Pliocene [*Medina-Elizalde et al.,* 2008; *O'Brien et al.,* 2014]. However, we do not correct for them here because (1) Mg/Ca$_{\text{seawater}}$ estimates for the Pliocene are poorly constrained and range widely (~2.7 to 5.5 mmol/mol, compared to the modern value of 5.17 mol/mol) [*Rausch et al.,* 2013] and (2) dramatic Mg/Ca$_{\text{seawater}}$ corrections result in strong disagreement between biomarker and Mg-/Ca-based SST proxies. SST records from EEP ODP Site 847 and a composite record from eastern equatorial Atlantic 662 and 663 based on foraminifera Mg/Ca (uncorrected for Mg/Ca$_{\text{seawater}}$) and $U^{K'}_{37}$ (independent of changes Mg/Ca$_{\text{seawater}}$), have parallel trends in temperature and are within calibration error [*Dekens et al.,* 2008; deMenocal et al., submitted to *Nature Geoscience*, 2015]. For EEP Site 847, eastern equatorial Atlantic Sites 662/663, and WEP Site 806, dramatic Mg/Ca$_{\text{seawater}}$ corrections, like that proposed recently by *O'Brien et al.* [2014], cause strong disagreement

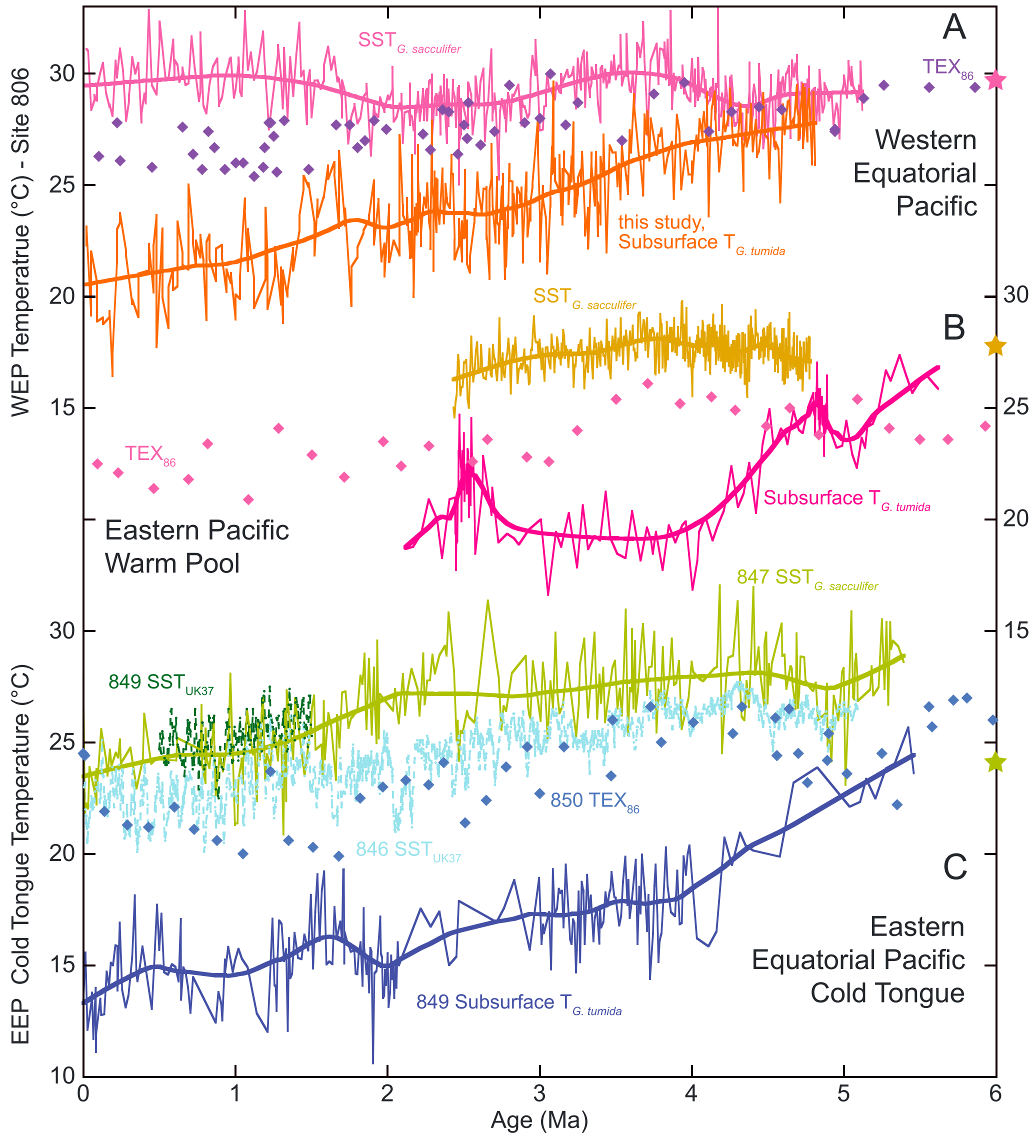

Figure 2. Temperature records from (a) *WEP* Site 806: $SST_{G.\ sacculifer}$ [*Wara et al.*, 2005], TEX_{86} [*Zhang et al.*, 2014], and subsurface $T_{G.\ tumida}$ [this study]; (b) *EPWP* Site 1241: $SST_{G.\ sacculifer}$ [*Groeneveld et al.*, 2006], TEX_{86} [*Seki et al.*, 2012], and subsurface $T_{G.\ tumida}$ [*Steph et al.*, 2006]; and (c) *Cold Tongue* Sites 846, 847, 849, and 850: $U^{K'}_{37}$ Site 846 [*Lawrence et al.*, 2006], $SST_{G.\ sacculifer}$ Site 847 [*Wara et al.*, 2005], $U^{K'}_{37}$ Site 849 [*McClymont and Rosell-Mele*, 2005], subsurface $T_{G.\ tumida}$ [*Ford et al.*, 2012], and TEX_{86} Site 850 [*Zhang et al.*, 2014]. Thick lines are locally weighted (20%) least squares smoothing. Stars indicate modern SST.

between records within each location; corrected Mg/Ca SST estimates are markedly warmer than $U^{K'}_{37}$ and TEX_{86} derived SSTs. Thus, $Mg/Ca_{seawater}$ corrections are likely to be small, accounting for only ~1°C warmer SST in the early Pliocene, and have minimal impact on the interpretations presented in this paper. Nevertheless, if the $Mg/Ca_{seawater}$ was elevated during the Pliocene relative to today (1) the cooling trend observed in subsurface temperature in the WEP and EEP from the Pliocene to today would likely be larger and (2) the surface and subsurface Mg/Ca-derived records may be differentially influenced by a change in $Mg/Ca_{seawater}$ [*Evans and Müller*, 2012], though this difference is likely to be small and would not greatly impact the calculated vertical or zonal gradients.

3.2. Cooling and/or Shoaling of the Equatorial Thermocline

During the early Pliocene, subsurface temperatures in the WEP were ~4°C warmer than the late Holocene (3.5–4.5 Ma average: 26.9°C; core top: 22.6°C [*Ford et al.*, 2015], Figure 1b). Subsurface temperatures

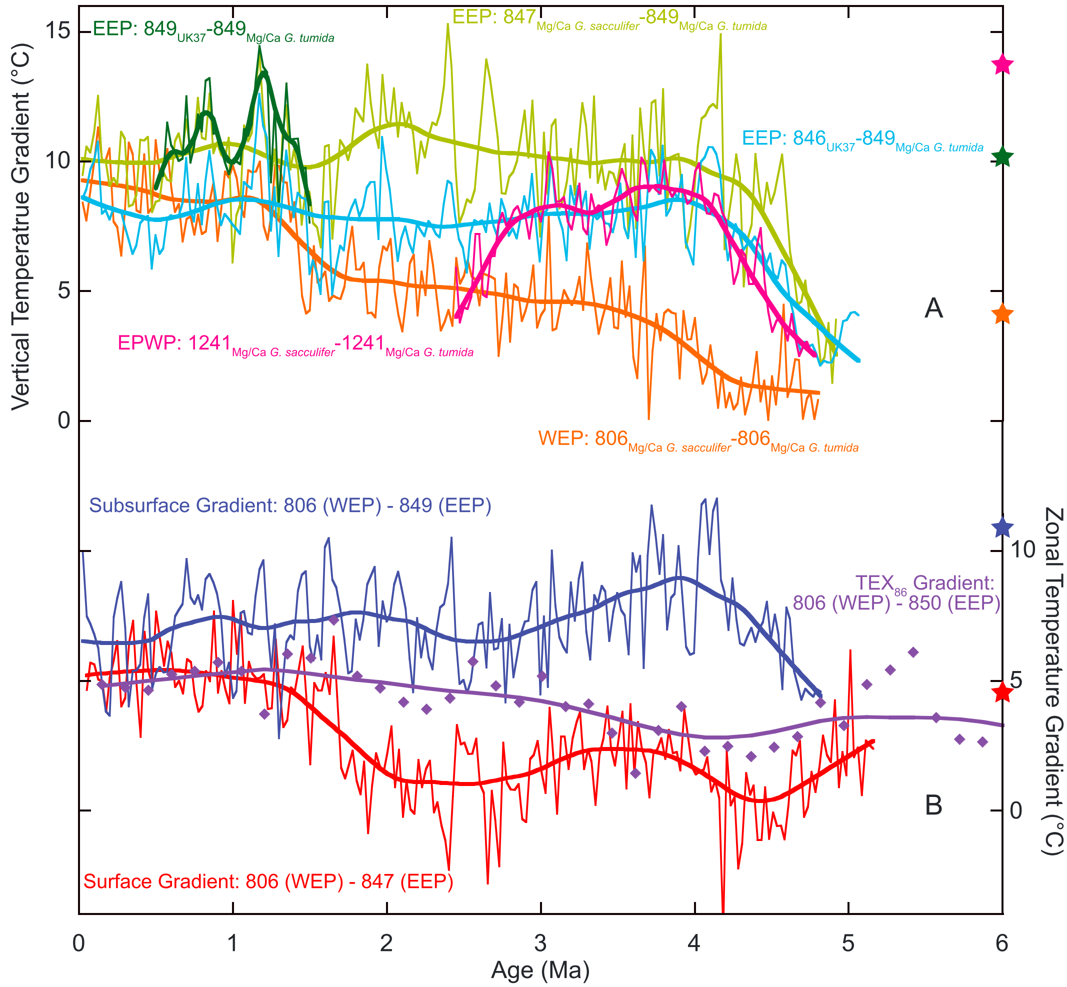

Figure 3. (a) $\Delta T_{surface\text{-}subsurface}$ from ODP Sites 806, 846, 847, 849, and 1241. (b) The zonal SST ($SST_{G.\ sacculifer}$, Sites 847 and 806) and subsurface temperature (subsurface $T_{G.\ tumida}$, Sites 849 and 806) gradients. The TEX_{86} gradient is influenced by changes in surface and subsurface temperature over the last 5 Myr. Thin lines represent a resampling of original records (0.25 Ma Gaussian weighted running mean) that were subtracted from one another. Thick lines are locally weighted (20%) least squares smoothing. Stars indicate modern temperature gradients (surface = 0 m and subsurface = 125 m).

gradually cooled from the early Pliocene to present, suggesting a long-term thermocline cooling and/or shoaling, which is supported by stable isotope [*Chaisson and Ravelo*, 2000; *LaRiviere et al.,* 2012] and faunal evidence [*Chaisson and Leckie*, 1993]. The WEP subsurface temperature record combined with EEP subsurface temperature records [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012] suggests that tropical thermocline adjustments were not isolated to the EEP. Rather, there was substantial subsurface cooling across the tropical Pacific from the Pliocene to today (Figure 1b) related to a long-term cooling and/or shoaling of the entire equatorial thermocline.

The $\delta^{13}C$ values of thermocline dwelling planktonic foraminifera support the interpretation that the long-term subsurface cooling trend in *G. tumida* is related to changing thermocline conditions rather than a change in its depth habitat [*Whitman and Berger*, 1993; *Cannariato and Ravelo*, 1997; *Steph et al.,* 2006, 2010; *Ford et al.,* 2012]. While subsurface temperatures cooled over the last 5 Ma [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012; this study], the $\delta^{13}C$ values of thermocline dwelling planktonic foraminifera increased [*Whitman and Berger*, 1993; *Cannariato and Ravelo*, 1997; *Ford et al.,* 2012]. If the cooling trend in *G. tumida*-derived temperatures were related to a deepening its depth habitat, then the opposite $\delta^{13}C$ trend would be expected because $\delta^{13}C$ values are lower at depth [*Cannariato and Ravelo*, 1997; *Ford et al.,* 2012]. Consequently, the subsurface temperature cooling from the Pliocene to present reflects tropical thermocline cooling and/or shoaling.

The depth of and stratification across the tropical thermocline is important to the ocean heat budget; shallow, wind-driven circulation balances heat gain in tropical upwelling regions and heat loss in high latitudes by altering the thermocline's depth [*Boccaletti et al.,* 2004]. Tropical and subtropical upwelling zones are areas of heat gain because incoming solar radiation is not balanced by local latent heat flux [*Boccaletti et al.,* 2004]. For example, in the EEP cold tongue, the shallow thermocline and upwelling brings cold water to the surface where a large amount of shortwave radiation is absorbed [*Talley*, 1984]. When the thermocline is shallow and/or cool (deep and/or warm), tropical heat gain is large (small). Consequently, heat gain in the tropics is influenced by the tropical thermocline depth, temperature, and vertical density structure [*Boccaletti et al.,* 2004]. EEP SSTs in the present-day cold tongue region were relatively warm during the early Pliocene [*Wara et al.,* 2005; *Lawrence et al.,* 2006] and imply reduced tropical ocean heat gain relative to today. A deep tropical thermocline during the early Pliocene, as suggested by the warm subsurface temperatures from the WEP (this study) and from the EEP [*Steph et al.,* 2006; *Ford et al.,* 2012], is consistent with theoretical studies [*Philander and Fedorov*, 2003; *Boccaletti et al.,* 2004] that predict that the equatorial thermocline should be deep when EEP cold tongue region is warm.

Equatorial thermocline waters are sourced in subtropical regions as part of the shallow overturning circulation [*Talley*, 2003; *Fiedler and Talley*, 2006]. Small changes in temperature and salinity in these subtropical regions impact thermocline depth and the character of the water that ultimately upwells along the equator [*Gu and Philander*, 1997; *Fedorov et al.,* 2007]. An expanded warm pool during the early Pliocene [*Brierley et al.,* 2009; *Karas et al.,* 2011] implies that source water regions for the equatorial thermocline were warm in comparison to today and that the tropical thermocline was warm, deep, and weakly stratified. This warm water then upwelled in the present-day cold tongue region, and thus, SSTs were relatively warm [*Wara et al.,* 2005; *Lawrence et al.,* 2006]. Dynamic feedbacks that are currently poorly represented in climate models, such as vertical mixing [*Fedorov et al.,* 2013] and cloud albedo [*Burls and Fedorov*, 2014], may have modified heat transport and/or heat gain and contributed to Pliocene thermocline warmth and depth.

4. The Impact of a Cooling and Shoaling Equatorial Thermocline

The long-term evolution of the tropical thermocline has implications for tropical Pacific climate over the last 5 million years because the mean climate state of the tropical Pacific is dynamically linked though the atmosphere, thermocline, and spatial SST patterns. Here we describe the tropical thermocline's influence on regional SST patterns and TEX_{86} proxy interpretations.

4.1. Regional SST Patterns

Today, the cold tongue has cool SSTs (~24°C) and is tightly coupled to the thermocline through wind-driven equatorial upwelling. $\Delta T_{\text{surface-subsurface}}$ is a relative measure of the coupling between surface and subsurface temperatures. When $\Delta T_{\text{surface-subsurface}}$ does not change with time, the surface and subsurface are changing in concert (or both stable) indicating tight coupling. Changes in $\Delta T_{\text{surface-subsurface}}$ indicates that the surface and subsurface are behaving independently of one another. During the early Pliocene, $\Delta T_{\text{surface-subsurface}}$ was small because the thermocline was deep and had little influence on SST (Figure 3). Between 4.8 and 4.0 Ma, $\Delta T_{\text{surface-subsurface}}$ steeply increased in the EEP largely due to subsurface cooling (Figure 1b), which could be related to regional thermocline shoaling possibly due to Panama Seaway closure [*Steph et al.,* 2006; *Ford et al.,* 2012; *Zhang et al.,* 2012]. This shoaling of the thermocline was a precondition for SST cooling in the EEP, which started at ~4 Ma (Figure 2c, particularly at Site 846) [*Ford et al.,* 2012]. After 4.0 Ma, $\Delta T_{\text{surface-subsurface}}$ in the EEP was relatively constant (Figure 3a), indicating SSTs in the cold tongue were intimately linked with subsurface conditions (i.e., when subsurface temperatures cooled, so did SSTs, Figures 2c and 3a); thus began the emergence of a modern-like cold tongue that is tightly coupled to the thermocline through upwelling. Over the last 4 myrs, subsurface temperatures continued to cool across the Pacific basin, suggesting long-term cooling and/or shoaling of the tropical thermocline, though it is difficult to distinguish between the two. As the tropical thermocline continued to cool and/or shoal and EEP SSTs continued to cool.

During the Pliocene, SSTs in the EPWP were similar to present day [*Groeneveld et al.,* 2006]. Although the EPWP shares a similar subsurface temperature history with the cold tongue, thermocline cooling/shoaling had no influence on SSTs (Figure 2b). Today, the thermocline is shallow in the EPWP, but weak winds

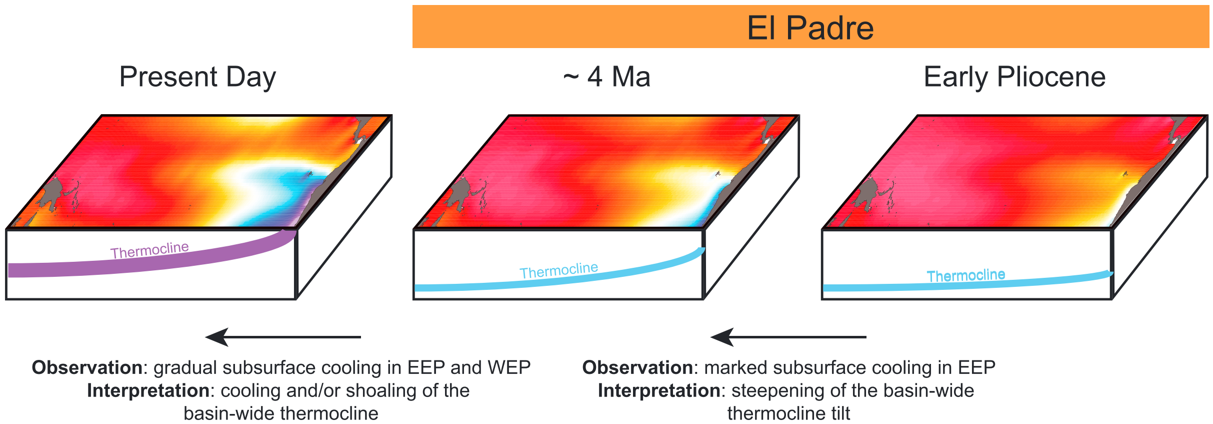

Figure 4. Schematic diagram of thermocline evolution from *El Padre* to present day.

prevent strong entrainment at the base of the surface mixed layer and the area is stratified with warm SSTs (~27 °C). Similarly, a deep thermocline combined with weak Hadley Circulation [*Brierley et al.,* 2009] would have had little influence on EPWP SSTs during the Pliocene.

Similar to the EPWP, the WEP warm pool Mg/Ca-derived SSTs were not impacted by the long-term changes in thermocline structure. Today in the WEP, equatorial upwelling has little influence on SSTs because the thermocline is deep and cold water is beyond the vertical reach of Ekman transport, though changes in subsurface temperatures may have a secondary influence on equatorial SSTs on glacial timescales [*Dyez and Ravelo*, 2012]. During the Pliocene, WEP warm pool SSTs were similar to today [*Wara et al.,* 2005; *Ravelo et al.,* 2014] and the thermocline cooled without concomitant changes in SST. The WEP $\Delta T_{\text{surface-subsurface}}$ suggests that the overall heat content and size of the warm pool has gradually decreased over the last 5 Ma (Figure 3).

4.2. Warm Subsurface Temperatures and TEX_{86} Proxy Interpretation

Substantial changes in subsurface temperature and thermocline warmth/depth documented in the WEP (this study) and the EEP [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012] influence the interpretation of the temperature proxy TEX_{86}. TEX_{86} represents a depth-integrated temperature signal (0–200 m) [*Wakeham et al.,* 2003], and thus, in the tropical Pacific where the temperature gradients in the upper 200 m can be large, has a spatially variable relationship with SST which necessitates a regional temperature calibration [*Tierney and Tingley*, 2014]. A TEX_{86} temperature calibration developed by *Tierney and Tingley* [2014] to account for the spatial heterogeneity in the TEX_{86}–SST proxy suggests there is a relationship between the steepness of the thermocline and TEX_{86} values. Where the thermocline is steep (e.g., tropical upwelling regions like the EEP, high latitudes), TEX_{86}-derived temperatures are too cold, suggesting subsurface TEX_{86} production. Within the EPWP (Site 1241, Figure 2b) and cold tongue region (Site 850, Figure 2c), core top and Pleistocene TEX_{86}–derived temperatures clearly have a cold bias in comparison to Mg/Ca and $U^{K'}_{37}$ SSTs, implying subsurface TEX_{86} production ($U^{K'}_{37}$ estimates are not plotted for Sites 1241 and 806 because the proxy may be saturated during the Pliocene) [*Ravelo et al.,* 2014]. This cold bias is minimized during the early Pliocene warm period when the thermocline is warm/deep and subsurface temperatures are warm [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012]. Similarly in the WEP, long-term subsurface cooling likely impacts the TEX_{86} values (Figure 2a). Given the evidence we present here for changing subsurface conditions, particularly in the EEP, TEX_{86} is inappropriate for quantitative reconstructions of zonal sea *surface* temperature gradients from the Pliocene to present day [*Ravelo et al.,* 2014] (Figure 3).

4.3. The Zonal SST Gradient and Thermocline Tilt

The tropical thermocline impact on cold tongue SSTs and the emergence of strong thermocline-SST coupling in the EEP around 4 Ma influenced ocean-atmosphere dynamics. Today, the strength and variability of Walker Circulation is tied to the zonal SST gradient. The balance of Mg/Ca and $U^{K'}_{37}$ SST estimates indicate the zonal SST gradient was reduced during the Pliocene in comparison to today [*Ravelo et al.,* 2014] (Figure 3). As warm pool temperatures have been relatively stable over the last 5 million years [*Ravelo et al.,* 2014], the gradual increase in the zonal SST gradient is driven by cold tongue SST cooling and consequently its coupling to the thermocline. Climate models indicate that the reduced zonal SST gradient during the Pliocene may have reduced Walker Circulation strength and affected the location of high/low pressure systems [*Brierley and Fedorov*, 2010; *Kamae et al.,* 2011]. For example, during the Pliocene, Africa was wetter and the Asian monsoon was stronger than today [*Kamae et al.,* 2011]. Additionally, the climate patterns associated with modern El Niño events are mostly present in equatorial and extratropical regions during *El Padre* [*Molnar and Cane,* 2002]. Over the last 4 Ma, as the thermocline cooled and/or shoaled, cold tongue SSTs cooled, the zonal SST gradient increased, Walker Circulation intensified and modern-like continental climates developed.

In addition to the zonal SST gradient, the equatorial thermocline tilt is important to tropical Pacific dynamics (e.g., El Niño–Southern Oscillation and Walker Circulation). Today, the equatorial Pacific mean state is characterized by a strong thermocline tilt [*Fiedler and Talley*, 2006]. The thermocline is deep in the west and shallow in the east, which results in a large zonal subsurface temperature gradient (~11.5°C at 125 m). During the earliest Pliocene (4.5 to 4.8 Ma) when the equatorial thermocline was warm and deep, the zonal subsurface temperature gradient was reduced (~5°C) suggesting the equatorial thermocline tilt was also weak (Figures 3 and 4). Coincident with rapid subsurface changes in the EEP [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012] at ~4.5 Ma Miocene thermocline taxa rapidly declined in the WEP and EEP [*Chaisson and Ravelo*, 2000]. At the same time that other thermocline dwellers radiated in the EEP, mixed-layer dwelling foraminifera expanded in the WEP, which suggests an increase in thermocline tilt [*Chaisson*, 1995; *Chaisson and Ravelo*, 2000]. The zonal subsurface temperature gradient (Figure 3) and the faunal assemblages [*Chaisson*, 1995; *Chaisson and Ravelo*, 2000] indicate the equatorial thermocline tilt has been relatively stable since 4.0 Ma, even as the basin-wide thermocline continued to cool and/or shoal (Figure 4). Though the equatorial thermocline tilt is an indicator of Walker Circulation strength [*DiNezio et al.,* 2011], additional high-latitude cooling may have been necessary to establish modern meridional and zonal SST gradients and initiate strong Walker Circulation at ~2 Ma [*Ravelo et al.,* 2004; *Martinez-Garcia et al.,* 2010].

5. Summary

Similar to modern El Niño conditions, the early Pliocene *El Padre* mean state included a reduced zonal SST gradient and weak thermocline tilt (Figure 4). *However,* unlike during an El Niño event, the *El Padre* mean state also included a warm, deep thermocline across the entire equatorial Pacific. The dynamics that initiate and propagate modern-day short-lived El Niño events are not the same as those responsible for large-scale mean state changes that contributed to *El Padre*. The fundamental changes in thermocline temperature and structure as documented by subsurface temperature trends in *G. tumida* [*Steph et al.,* 2006, 2010; *Ford et al.,* 2012; this study], $\Delta T_{\text{surface-subsurface}}$ (this study), and foraminifera assemblages [*Chaisson and Ravelo*, 2000] indicate that the subsurface was warm, the thermocline was warm/deep and the thermocline tilt was reduced during the early Pliocene (Figure 3). At ~4.0 Ma, the tropical thermocline shoaled, thereby influencing EEP cold tongue SSTs, and thereafter, cold tongue SSTs and the thermocline became atmospherically coupled. In the WEP, thermocline shoaling and/or cooling was not sufficient to greatly impact SSTs in that region. The tropical thermocline and its influence on the global heat budget contributed to Pliocene warmth. As the thermocline cooled/shoaled over the last 4 million years, it played a decisive role tropical ocean-atmosphere dynamics, particularly in the cold tongue, and may have contributed to the transition from the warm Pliocene to the cold Pleistocene.

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