



# Evolution of the zonal gradients across the equatorial Pacific during the Miocene–Pleistocene

Catherine Beltran, Gabrielle Rousselle, Marc de Rafélis, Marie-Alexandrine Sicre, Nathalie Labourdette, Stefan Schouten

## ► To cite this version:

Catherine Beltran, Gabrielle Rousselle, Marc de Rafélis, Marie-Alexandrine Sicre, Nathalie Labourdette, et al.. Evolution of the zonal gradients across the equatorial Pacific during the Miocene–Pleistocene. *Journal of Sedimentary Research*, 2019, 89 (3), pp.242-252. 10.2110/jsr.2019.15 . insu-02104911

**HAL Id: insu-02104911**

**<https://insu.hal.science/insu-02104911>**

Submitted on 13 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Running head: Evolution of the Equatorial Pacific mean state over the last 10 Myr

Title: Evolution of the zonal gradients across the Equatorial Pacific during the Miocene-  
Pleistocene

CATHERINE BELTRAN<sup>1,3</sup>, GABRIELLE ROUSSELLE<sup>1</sup>, MARC DE RAFÉLIS<sup>2</sup>, MARIE-  
ALEXANDRINE SICRE<sup>4</sup>, NATHALIE LABOURDETTE<sup>1</sup>, STEFAN SCHOUTEN<sup>5,6</sup>

<sup>1</sup>Sorbonne Universités (UPMC, Université Paris 06), UMR 7193, IStEP, Case Postale 116 - 4, place  
Jussieu 75005 Paris, France.

<sup>2</sup>Université Paul Sabatier, UMR 5563, Géosciences Environnements Toulouse - 14, avenue Edouard  
Belin 31400 Toulouse, France.

<sup>3</sup>Department of Marine Science, University of Otago, PO Box 56, Dunedin 9054, New Zealand.  
Present address. **Corresponding author: catherine.beltran@otago.ac.nz**

<sup>4</sup>Sorbonne Universités (UPMC, Université Paris 06)-CNRS-IRD-MNHN, LOCEAN Laboratory, 4  
place Jussieu, F-75005 Paris, France.

<sup>5</sup>NIOZ Royal Netherlands Institute for Sea Research, Department of Marine Microbiology and  
Biogeochemistry, and University of Utrecht, P.O. Box 59, 1790 AB Den Burg (Texel), The  
Netherlands

<sup>6</sup>Departement of Earth Sciences, Utrecht University, Heidelberglaan 8, 3584 CS Utrecht, The  
Netherlands

## ABSTRACT

Combining  $U_{37}^{k'}$  - and  $TEX_{86}$ -derived temperatures, and oxygen isotopic values of mixed-  
layer and thermocline species from the IODP site U1338 (East Equatorial Pacific) and ODP  
Site 806 (West Equatorial Pacific) we assess the evolution of the zonal sea-surface  
temperature gradients and thermocline depth across the equatorial Pacific from the Late

Miocene through the Pleistocene. Data suggest a long-term shoaling of the thermocline along the equator throughout the Miocene-Pliocene that accelerated around 5.3 Ma. We identify a critical transition at about 3.8 Ma from a El-Niño-like-dominated mean state during the Late Miocene and Early Pliocene to a La-Niña-like-dominated state during the Late Pliocene-Pleistocene. This transition coincides with the restriction of the Indonesian seaway and the onset of ice growth in the northern hemisphere and in Antarctica that led to the long-term strengthening of the Walker circulation and affected low-latitude zonal gradient.

**KEY WORDS:** Equatorial Pacific, Miocene Pliocene climate, biomarker proxies, planktonic foraminifera, coccoliths.

## INTRODUCTION

The equatorial Pacific Ocean plays an important role in the global climate by influencing the heat transport from low to mid- and high latitudes. The modern structure of the equatorial Pacific is characterized by a pronounced east-west asymmetry of the thermocline depth and of sea-surface temperature (SSTs) with the warm pool ( $\sim 29^{\circ}\text{C}$ ) in the west and the cold tongue ( $\sim 23^{\circ}\text{C}$ ) in the east (Fig. 1). The thermocline in the West Equatorial Pacific is deep and controls the flux of atmospheric latent heat (Tian et al., 2001) whereas in the east it is shallow and heat is absorbed (Boccaletti et al., 2004). The SSTs across the equatorial Pacific are affected by the El Niño–Southern Oscillation (Cane, 1998), one of the most important component of the global climate system, which alternates at inter-annual time scale between warm “El Niño” and cold “La Niña” phases.

The El Niño–Southern Oscillation is sensitive to the SST distribution across the equatorial Pacific through the link between temperatures and the strength of the trade winds (Neelin et

al., 1998). Changes in the meridional SST gradient in the equatorial Pacific have important consequences on the local and global climate.

The modern setting of the equatorial Pacific was established during the mid- to late Miocene (LaRivière et al., 2012) through the progressive closure of the Central American Seaway (CAS) and the Indonesian Seaway (Keigwin, 1982; Haug and Tiedemann, 1998; Srinivasan and Sinha, 1998; Schneider and Schmittner, 2006) together with Northern Hemisphere Glaciation (Mudelsee and Raymo, 2005) (Fig. 2). During this period, the onset of the modern thermohaline circulation and equatorial upwelling led to the progressive cooling of deep - water (Woodruff and Savin, 1989; Ravelo et al., 2004), upper-ocean stratification, and thermocline rise. Nathan and Leckie (2009) dated the proto warm pool in the West Equatorial Pacific (WEP) between 11.6 and 10 Ma. The thermocline depth asymmetry set up around 4.8 Ma and induced a well-documented cold-water tongue in the Eastern Equatorial Pacific (EEP) between 4.4 and 3.6 Ma (Chaisson and Ravelo, 2000; Wara et al., 2005; Steph et al., 2010; Rousselle et al., 2013).

Although numerous studies (e.g., Raymo et al., 1996; Haywood and Valdes, 2004; Ravelo et al., 2004, 2006; Rickaby and Halloran, 2005; Wara et al. 2005; Barreiro et al., 2005; Fedorov et al. 2006, 2013; Dekens et al. 2008; Brierley et al., 2009) established that the equatorial Pacific zonal gradients were weaker during the early Pliocene warm period (El Niño-like, El Padre) and stronger during the mid-Holocene (La Niña-like; Koutavas et al. 2006), there is no consensus on the long-term evolution of the equatorial Pacific mean state since the Miocene (Fig. 2). This is a major limitation to predict El Niño–Southern Oscillation, in that its behavior is closely related to long-term changes in tropical Pacific oceanography that are still not fully understood. Some authors suggest that the equatorial thermal state remained unchanged over the last 12 Myr (Zhang et al., 2014) whereas others identified alternating El Niño-like and La Niña-like conditions (Wara et al., 2005; Ravelo et al., 2006; Nathan and

Leckie, 2009; Kamikuri et al., 2009; Drury et al., 2018) or a progressive shoaling of the thermocline over the last 13 Myr (LaRiviere et al., 2012).

Because the past variability of the equatorial Pacific mean state is also considered to have played a role in major climatic transitions (Yin and Battisti, 2001), reconstructing the long-term evolution of the thermal structure in this region is crucial.

While most published studies focus on very specific time intervals (e.g., Medina-Elizalde and Lea, 2010; Ford et al., 2015), the purpose of this study is to examine the long-term evolution of equatorial Pacific surface conditions over the last 10 Myr. To do so, surface and subsurface temperature records from IODP Site U1338 (EEP) (Fig. 1) are generated from both alkenones ( $U_{37}^{k'}$ ) produced by coccolithophores (marine unicellular haptophyte algae, Brassell et al., 1986) and glycerol- dialkyl glycerol- tetraethers (GDGTs,  $TEX_{86}^H$ ) produced by *Thaumarchaeota* (Archaea, Schouten et al., 2002; Kim et al., 2010). Additional hydrological information is provided by the oxygen-isotope composition of calcareous nannofossils *Noelaerhabdaceae* spp. calcifying in the photic zone and the thermocline-dweller foraminifera *Globorotalia menardii* (Martin, 1999; Spero et al., 2003) recovered from the ODP Site 806 (WEP) and IODP Site U1338 (Fig. 1).

## OCEANOGRAPHIC SETTING

The equatorial Pacific surface ocean circulation, controlled by the Walker cell and Trade winds, results in two westward surface currents, the North and South Equatorial Currents, respectively (SEC and NEC; Fig. 1). The easterly winds pile warm waters in the WEP and create a subsurface eastward circulation known as the Equatorial Under Current (EUC), which brings cold and nutrient-rich waters to the surface in the EEP. The subsequent thinning of the mixed-layer and formation of a cold tongue in the EEP produce a strong W-E asymmetry of the equatorial thermocline depth, deeper in the West Pacific than in the East Pacific (Fig. 1). The modern equatorial SST gradient across the Pacific varies in response to

the inter-annual El Niño-Southern Oscillation. During El Niño years, the trade winds weaken, the thermocline deepens in the EEP, and the equatorial upwelling attenuates. As a consequence, the equatorial SST gradient is reduced, mean temperatures are warmer, and the extratropical heat distribution is impacted (Molnar and Cane, 2002; McPhaden et al., 2006). Since the Miocene, the Pacific zonal temperature gradients and the thermocline tilt have varied. Extended periods of reduced equatorial SST gradient and deep thermocline that mimic the modern El Niño events are called permanent El Niño-like states. Similarly, periods of long-term strong equatorial Pacific zonal gradients are called La Niña-like states.

## **MATERIALS AND METHODS**

### *IODP Site U1338 and ODP Site 806*

The IODP Site U1338 (2° 30.469' N, 117° 58.178' W, 4200 meters water depth, leg 321) was drilled in the EEP, in the modern cold tongue (Pälike et al., 2010) (Fig. 1). Despite the northward drift of the Pacific plate, this site remained in the equatorial band for the past 10 Myr (Pälike et al., 2010). Sediments at Site U1338 were deposited above the calcite compensation depth (Pälike et al., 2012) and are composed of well-preserved biogenic material, predominantly nannofossil oozes, with variable abundances of diatoms, radiolarians, and foraminifera (Pälike et al., 2010). The age model of the core was constructed from biostratigraphic (nannofossils, foraminifers, diatoms, and radiolarians) and paleomagnetic data (Pälike et al., 2010; Backman et al., 2016). Average sedimentation rates are relatively high for the studied time interval (~ 27 m/Myr).

ODP Site 806 (0° 19,1' N, 159° 21,7' E, 2520 meters water depth, leg 130) is located on the northeast margin of the Ontong Java plateau in the area of the WEP warm pool (Fig. 1). Sediments are composed mostly of well-preserved calcareous nannofossils and planktic foraminifera. The age model is based exclusively on biostratigraphic data of calcareous nannofossils, foraminifera, diatoms, and radiolarians established by Kroenke et al. (1991),

later refined by Takayama (1993) and Chaisson and Leckie (1993). Ages are corrected based on biostratigraphic data of Backman et al. (2016) (see Supplement). The average sedimentation rate at this site is higher than at U1338, ranging from ~ 45 m/Myr between 9 and 5 Ma to ~ 29 m/Myr during the Pliocene.

Proxy records at both sites are generated for the period between 10 and 0.18 Ma using samples from sections U1338B-22H7W through U1338B-1H2W and sections 806B-37X3W through 806B-1H1W. The average sampling resolution of these records varies between 100 kyr and 400 kyr.

#### *Oxygen Stable-Isotope Measurements*

To determine changes in the thermocline depth in the EEP and WEP through time, we measured the oxygen-isotope ratios ( $\delta^{18}\text{O}$ ) in the calcite of calcareous-nannofossil-enriched fractions and of the upper-thermocline-dweller planktonic foraminifera *Globorotalia menardii*. Calcareous nannofossils calcify mainly in the photic zone and thus are used to derive surface-water properties (Roth, 1986) whereas *G. menardii* is selected to assess subsurface water changes.

$\delta^{18}\text{O}$  values are measured on calcareous nannofossils *Noelaerhabdaceae* spp. isolated from the bulk sediment following the procedure of Minoletti et al. (2009).  $\delta^{18}\text{O}$  measurements are performed on the 2-5  $\mu\text{m}$  fractions at both sites. For site U1338, we use the  $\delta^{18}\text{O}$  data previously published by Rousselle et al. (2013) based on the same protocol as in the present study.  $\delta^{18}\text{O}$  values are measured using a Finnigan Delta E mass spectrometer at 50°C, at a temporal resolution of 400 kyr. The quality of the granulometric separation based on 200 particles counting in smear slides is estimated to be at least 75% except between 8 and 9 Ma at Site 806, where *Sphenolitus abies* dominated. These measurements are thus not considered here. In addition, five to seven specimens of *G. menardii* were hand-picked from the > 160  $\mu\text{m}$  fractions for isotopic measurements. Analyses are performed on a VG ISOPRIME at 90°C

with a precision of 0.1‰ and expressed with reference to the VPDB international standard. 45 samples at Site U1338 and 99 samples at Site 806 were analyzed. The average temporal resolution over the last 10 Myr is comprised between 120 and 150 ka.

#### *Alkenone Analyses*

Alkenone-derived SSTs of Site U1338 previously reported by Rousselle et al., (2013) are supplemented in the present study with 23 additional samples selected from the Pliocene interval (U1338B-8H5W to U1338B-1H2W) to reach a temporal resolution of 100 kyr. Sedimentary alkenones are analyzed following the procedure described by Ternois et al. (2000). About 5 g of freeze-dried sediments are extracted in a mixture of CH<sub>2</sub>Cl<sub>2</sub> / CH<sub>3</sub>OH. Alkenones are isolated from the total lipid extract by silica-gel chromatography using solvents of increasing polarity. The fraction containing alkenones is concentrated, transferred into clean glass vials, and evaporated under a nitrogen stream. Gas-chromatography analyses are performed using a Varian 3400CX series equipped with a septum programmable injector (SPI) and a flame ionization detector (FID). We use a fused silica capillary column (Chrompack CP Sil5CB, 50 m long, 0.32 mm internal diameter, 0.25 μm film thickness) and helium as a carrier gas. The alkenone unsaturation ratio  $U^{K'}_{37}$  ( $C_{37:2}/(C_{37:2} + C_{37:3})$ ) is converted into SSTs using the Conte et al. (2006) calibration:  $T = -0.957 + 54.293 (U^{K'}_{37}) - 52.894 (U^{K'}_{37})^2 + 28.321 (U^{K'}_{37})^3$ , which provides more accurate estimates in warm-temperature range than Prahl et al. (1988). Average external precision of the SSTs using this calibration has been estimated at ~ 1.2°C (Conte et al., 2006). Replicate analyses indicate internal precision of ± 0.5°C. Because of the limited amount of sediment material at Site 806 (where alkenone concentrations are extremely low), previously published data from Pagani et al. (2010) provide data covering the past 5 Myr. Note that we recalculated SSTs from the  $U^{K'}_{37}$  values of Pagani et al. (2010) using the Conte et al. (2006) calibration to avoid calibration bias between sites (see Supplement).



Forty samples from Site U1338 were analyzed for GDGTs at the Netherlands Institute for Sea Research (NIOZ, Texel, The Netherlands). About 5 g of sediment are freeze dried and extracted in a mixture of CH<sub>2</sub>Cl<sub>2</sub> and CH<sub>3</sub>OH. The total lipid extracts are separated following the protocol described in Schouten et al. (2002), using Al<sub>2</sub>O<sub>3</sub> column chromatography to separate non-polar compounds from the polar GDGTs. Polar fractions are then filtered through a 0.4 µm pore-size filter, evaporated under nitrogen, and diluted to a concentration of 2 mg/ml. GDGTs are analyzed using an Agilent HP1100 (HPLC) equipped with a Prevail Cyano column (3 µm, 150 mm x 2.1 mm) following Schouten et al. (2007). The TEX<sub>86</sub> index is calculated using peak areas of the following GDGTs as defined by Schouten et al. (2002):  $TEX_{86} = [GDGT2] + [GDGT3] + [GDGT5'] / [GDGT1] + [GDGT2] + [GDGT3] + [GDGT5']$ . The TEX<sup>H</sup><sub>86</sub>, defined as the log(TEX<sub>86</sub>), is used to calculate temperatures over the past 9 Myr. Temperatures are calculated using the calibration established for temperatures above 15°C by Kim et al. (2010) ( $T = 68.4 * TEX^H_{86} + 38.6$ ). The error on temperature estimates is ± 2.5°C. Other calibrations have been proposed for TEX<sub>86</sub> temperatures, in particular based on Bayesian statistics (Tierney and Tingley, 2015) but these yield results similar to those shown here, whereas the Kim et al. (2010) calibration is consistent with other studies from this area (e.g., Seki et al., 2010; Zhang et al., 2014). TEX<sup>H</sup><sub>86</sub> - derived temperatures are obtained at a mean temporal resolution of 230 kyr. At Site 806, because of the very low GDGT concentrations, we use previously published data from Zhang et al. (2014) covering the past 12 Myr for comparison with the data from Site U1338.

## RESULTS

### *Stable Isotopes of the Calcareous Nannofossil Fine Fractions and G. menardii*

#### **δ<sup>18</sup>O Record at Site U1338.---**

The oxygen stable-isotope signatures of the *Noelaerhabdaceae*-enriched fine fractions ( $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$ ) vary between -1.5‰ and 0.5‰ (Fig. 3A).  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  progressively increase between 8 Ma and 5 Ma, before declining to -1.3‰ until 2.7 Ma and rising again to 0.4‰. The  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  record is similar to the higher resolution  $\delta^{18}\text{O}$  record of the surface dweller *G. sacculifer* from the nearby Site 847 covering only the last 5 Myr (Wara et al., 2005) (Figs. 1, 3A).

$\delta^{18}\text{O}$  values measured on the thermocline-dwelling planktonic foraminifera *G. menardii* ( $\delta^{18}\text{O}_{\text{G.menardii}}$ ) over the last 8 Myr (Figure 3A) demonstrate that values vary between -1.4‰ and 1.25‰ and display trends similar to those of  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  until 5 Ma. Then,  $\delta^{18}\text{O}_{\text{G.menardii}}$  become more positive than  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  and still increase until 0.4 Ma, as also recorded in the deep thermocline dweller *G. tumida*  $\delta^{18}\text{O}$  values ( $\delta^{18}\text{O}_{\text{G.tumida}}$ ) at Site 847 (Figs. 1, 3A; Wara et al., 2005).

#### **$\delta^{18}\text{O}$ Record at Site 806.---**

$\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  at site 806 vary within a range similar (between -2.8 and 0.9‰) to site U1338 (Fig. 3B).  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  values are relatively stable (around 0‰) between 7 Ma and 4.4 Ma and rapidly decline to more negative values between 4.5 Ma and 4 Ma, after which values remain stable until 0.38 Ma. The  $\delta^{18}\text{O}_{\text{G.menardii}}$  record at Site 806 shows a long-term decrease between 9.7 Ma and 7 Ma and becomes stable until 1.9 Ma. At 3.7 Ma oxygen-isotope values decrease sharply by 1‰, and again between 2.5 Ma and 1.8 Ma. The  $\delta^{18}\text{O}_{\text{G.menardii}}$  values then increase to higher values (-0.4 ‰) until 0.5 Ma and further to 0.5‰ at 0.2 Ma. Overall,  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  and  $\delta^{18}\text{O}_{\text{G.menardii}}$  reveal more positive values in the EEP than in the WEP and include larger-amplitude variations.

#### *EEP Temperature Reconstructions.*

Alkenone-derived SSTs ( $\text{SST}_{\text{U}^{K'37}}$ ) at Site U1338 are relatively stable and warm ( $\sim 27^\circ\text{C}$ ) between 10 Ma and 6.8 Ma (Fig. 4A). They cool by  $1^\circ\text{C}$  between 6.8 Ma and 5.6 Ma, and

show a broad warming until 3.7 Ma. From 3.7 Ma onwards, SSTs depict another cooling of about 4°C and superimposed cold episodes of 1 to 2°C amplitude around 2.9 Ma, 1.7 Ma, and 0.5 Ma.

From the Late Miocene to the Pleistocene, TEX<sub>86</sub>-derived temperatures ( $T_{\text{TEX}}$ ) indicate a long-term cooling. Between 8 and 5 Ma,  $T_{\text{TEX}}$  and the SST<sub>U<sup>K'</sup>37</sub> vary in the same range of values (between 24°C and 27°C; Fig. 4A), although they are slightly cooler. From approx. 4.5 Ma, the two temperature proxies show marked temperature difference. Note that  $T_{\text{TEX}}$  increase around 7.5 Ma and 4.8 Ma, reaching values close to SST<sub>U<sup>K'</sup>37</sub>.

SST<sub>U<sup>K'</sup>37</sub> at Site U1338 are warmer than  $T_{\text{TEX}}$  by 2 to 3°C on average. Both progressively cool down between 9 Ma and 0.18 Ma but  $T_{\text{TEX}}$  decreases by 5°C while SST<sub>U<sup>K'</sup>37</sub> cools by only 3°C (Fig. 4A).

## DISCUSSION

### *Surface and Subsurface Water Temperatures in the Equatorial Pacific*

Warmer SST<sub>U<sup>K'</sup>37</sub> than  $T_{\text{TEX}}$ , as observed at Site U1338, is reported in several studies (e.g., Huguet et al., 2007; Lee et al., 2008; Leider et al., 2010; Lopes dos Santos et al., 2010; Rommerskirchen et al., 2011; Seki et al., 2012; Zhang et al., 2014) and explained by different depth habitat or season of production. However, because seasonality is weak at low latitudes, it is unlikely to explain a temperature differences of up to 4°C, at Site U1338. Unlike haptophytes thriving in the photic zone, *Thaumarchaeota*, the sources of the GDGTs, occur throughout the water column (e.g., Karner et al., 2001; Huguet et al., 2007), and the export of GDGTs can be integrated for a larger part of the upper part of the ocean, likely including a part of the thermocline. Wuchter et al. (2005) reported maximum concentrations of GDGTs between 100 and 200 m depth in the Pacific Ocean, coinciding with high ammonium concentrations below the photic zone (Murray et al., 1999; Karner et al., 2001; Wuchter et al., 2005; Huguet et al., 2007; Pearson et al., 2007). GDGT producers can thus preferentially

250 develop in subsurface or deeper waters (Huguet et al., 2007; Kim et al., 2008; Lee et al.,  
 251 2008; Huguet et al., 2011; Kim et al., 2012). The difference between  $T_{\text{TEX}}$  and  $\text{SST}_{\text{U}^{K'}_{37}}$  in the  
 252 EEP may then account for different production or export depth (Lopes dos Santos et al., 2010;  
 253 Rommerskirchen et al., 2011; Schouten et al., 2013).

254 The interpretation of  $T_{\text{TEX}}$  temperatures across the equatorial Pacific is complicated by both the  
 255 upwelling in the EEP and the different trophic conditions between the EEP and the WEP that  
 256 influence the export depth of GDGTs (Seki et al., 2012). Numerous studies indicate that  
 257 upwelling impacts on the depth of production and export of GDGTs to the sediment (Wuchter  
 258 et al., 2005; Huguet et al., 2007; Lee et al., 2008; Lopes dos Santos et al., 2010; Seki et al.,  
 259 2012). In the absence of upwelling,  $T_{\text{TEX}}$  reflects the surface temperatures (Sinninghe Damsté  
 260 et al., 2002; Wakeham et al., 2004) whereas under upwelling conditions,  $T_{\text{TEX}}$  represent  
 261 thermocline temperatures (Wakeham et al., 2002; Wuchter et al., 2005; Huguet et al., 2007).  
 262 Furthermore, the nitrate maximum across the modern equatorial Pacific exhibits a clear  
 263 asymmetry in the depth. Könneke et al. (2005) found that the production of *Thaumarchaeota*  
 264 occurs in the subsurface nitrate maximum, which thus is deeper in oligotrophic regions such  
 265 as the WEP (Brzezinski, 1988). As a consequence, within the same basin  $T_{\text{TEX}}$  may reflect  
 266 surface and subsurface conditions in response to different environmental factors (Hertzberg et  
 267 al., 2016).

268 In the EEP, the  $T_{\text{TEX}}\text{-SST}_{\text{U}^{K'}_{37}}$  temperature gradient ( $\Delta T$ ) is proposed to monitor changes of  
 269 the thermocline depth (Seki et al., 2012) assuming that  $\Delta T$  is driven by the depth migration of  
 270 GDGT producers in response to upwelling activity. Therefore, at Site U1338, warming  $T_{\text{TEX}}$   
 271 and reduced  $\Delta T$  reflect a deep thermocline and surface export of GDGTs, whereas a more  
 272 pronounced cooling of  $T_{\text{TEX}}$  compared to  $\text{SST}_{\text{U}^{K'}_{37}}$ , (increased  $\Delta T$ ) reflects a shallow  
 273 thermocline, upwelling activity, and subsurface export of GDGTs.

274 In the WEP, the interpretation of  $T_{\text{TEX}}\text{-SST}_{\text{U}^{K'}_{37}}$  is not straightforward either. At Site 806,  
 275  $\text{SST}_{\text{U}^{K'}_{37}}$  calculated from Pagani et al., (2010) are warm and stable, averaging 28 to 28.5°C  
 276 over the last 5 Myr (Fig. 4C) except for a 2°C sharp cooling at ~ 1.5 Ma. High-resolution  
 277 Mg/Ca-derived SSTs ( $\text{SST}_{\text{Mg/Ca}}$ ) corrected from Mg/Ca<sub>seawater</sub> (Medina-Elizalde et al., 2008)  
 278 from the same site show markedly warmer conditions in the surface of the WEP especially  
 279 between 5 and 3.5 Ma, reaching up to 32°C. This difference with the alkenone-derived  
 280 temperatures can be attributed to (1) the alkenone calibration being less accurate in the  
 281 warmer temperature range (Conte et al., 2006), thus leading to the underestimation of  
 282  $\text{SST}_{\text{U}^{K'}_{37}}$  (Tierney and Tingley 2018) or (2) the uncertainties on the seawater Mg/Ca  
 283 correction. However, from 3 Ma onwards,  $\text{SST}_{\text{U}^{K'}_{37}}$  and  $\text{SST}_{\text{Mg/Ca}}$  temperatures display  
 284 similar trends and values, except between 1.8 Ma and 1.2 Ma, when they diverge. Since this  
 285 discrepancy coincides with isotopic changes (Fig. 3) we can reasonably conclude that the  
 286 difference between the two records during the late Pliocene reflects oceanographic changes.  
 287 During the early Pliocene, cooler  $\text{SST}_{\text{U}^{K'}_{37}}$  appear to be linked to a calibration limitation of  
 288 the proxy at warm temperatures.

289 Comparison between the  $T_{\text{TEX}}$  record (Zhang et al., 2014) and subsurface temperatures  
 290 derived from Mg/Ca<sub>*G.tumida*</sub> (Ford et al., 2015) at ODP Site 806, highlights that from 5 to 3.5  
 291 Ma both reconstructions agree well within their uncertainties (Fig. 4C). From 3.5 to 2 Ma,  
 292  $T_{\text{TEX}}$  match with  $\text{SST}_{\text{U}^{K'}_{37}}$  and Mg/Ca-derived SSTs from the surface dweller *G. ruber*  
 293 (Mg/Ca<sub>*G.ruber*</sub> Medina-Elizalde et al., 2008), whereas Mg/Ca<sub>*G.tumida*</sub> temperatures are  
 294 systematically cooler than  $T_{\text{TEX}}$  (Fig. 4C). After 1.3 Ma,  $T_{\text{TEX}}$  values are intermediate between  
 295 Mg/Ca<sub>*G.ruber*</sub> and Mg/Ca<sub>*G.tumida*</sub> temperatures, while  $\text{SST}_{\text{U}^{K'}_{37}}$  tend to agree with Mg/Ca<sub>*G.ruber*</sub>  
 296 SSTs. It is likely that in the WEP, the  $T_{\text{TEX}}$  reflect production in different water depth in  
 297 response to trophic changes and environmental conditions. We speculate that during the warm  
 298 early Pliocene and after 1.3 Ma,  $T_{\text{TEX}}$  reflect subsurface conditions and that during the Late

Pliocene, the export of GDGTs derived mainly from surface waters. This interpretation nuances the interpretations of Zhang et al. (2014), who considered that  $T_{\text{TEX}}$  reflect surface temperatures and could be used as an alternative to  $U^{\text{K}'}_{37}$  under warm conditions.

#### *Changes in the Equatorial Pacific Mean State over the Last 10 Myr*

To investigate the evolution of the surface stratification across the Equatorial Pacific, we calculate the oxygen-isotope gradients between *Noelaerhabdaceae* and *G. menardii* ( $\Delta\delta^{18}\text{O}$ ) (Fig. 4B) (Nathan and Leckie, 2009; Beltran et al., 2014). Note that in doing so, the sea-water  $\delta^{18}\text{O}$  component is factored out. Higher (lower)  $\Delta\delta^{18}\text{O}$  values reflect a shallower (deeper) thermocline (Ravelo and Fairbanks, 1992; Ravelo and Shackleton, 1995; Farrell et al., 1995; Nathan and Leckie, 2009, Beltran et al., 2014).

Variations in the gradient between  $T_{\text{TEX}}$  and  $\text{SST}_{U^{\text{K}'}_{37}}$  also can be used to evaluate changes in the thermocline depth.  $T_{\text{TEX}}$  and  $\text{SST}_{U^{\text{K}'}_{37}}$  values similar to those observed between 7.3 Ma and 6.8 Ma, and around 4.8 Ma at IODP Site U1338, indicate a deep thermocline (Fig. 4A). Some intervals are characterized by an increase in  $\Delta T$  (such as, for example, between 6.8 Ma and 5.3 Ma at IODP Site U1338) associated with a cooling trend of both proxies. These features indicate that GDGTs are produced deeper and that surface waters are concomitantly cooling, which is consistent with upwelling activity.

Based on temperatures and isotopic gradients between surface and subsurface waters from the EEP and WEP, the data reveal a pronounced oceanographic change at *ca.* 5 Ma with the thermocline progressively rising (Fig. 4A, 4B).

#### **Late Miocene [9 – 5.3 Ma] Interval.---**

During the late Miocene period, east and west  $\Delta\delta^{18}\text{O}$  are reduced and stable, indicating a deep thermocline across the equatorial Pacific (Fig. 4B). From 10 Ma to 6.3 Ma, data indicate warm SSTs ( $\sim 27^\circ\text{C}$ ) in the EEP (Fig. 4A). This result coincides with the low abundances of upwelling radiolarian species reported between 9 and 7 Ma by Kamikuri et al. (2009). Similar

SST<sub>U<sup>K</sup>37</sub> and T<sub>TEX</sub> values at U1338 between 7.3 and 6.8 Ma also is consistent with a thick mixed layer in the EEP (Fig. 4A; Seki et al., 2012). In the WEP, Nathan and Leckie (2009) reported a similar decrease in the abundance of surface dwellers in favor of thermocline species, which suggests a deep thermocline. This reduced zonal gradient in SSTs and thermocline tilt across the equatorial Pacific corresponds to El Niño-like conditions, in agreement with earlier findings of Herbert et al. (2016), who indicate an expanded and weak Hadley circulation before 8 Ma.

The long-term Late Miocene El Niño-like state was interrupted by a brief interval (6.5 - 5.3 Ma) during which the thermocline shoaled in the EEP, as shown by the  $\delta^{18}\text{O}$  gradient (Fig. 4B). The SST cooling and decrease of surface salinity recorded at Site U1338 (Rousselle et al., 2013), supported by higher abundances of upwelling siliceous species during this interval (Kamikuri et al., 2009), suggest the first establishment of the cold tongue and of upwelling in the EEP. Increasing abundances of surface-dweller species at Site 806 (Nathan and Leckie, 2009) (Fig. 3 and 4), this interval further supports the idea of a weak and transient La Niña like period. Drury et al. (2018) suggested a cooling of the thermocline waters related to the global late Miocene cooling (Federov et al., 2006; Drury et al., 2017). Although the data do not rule out this hypothesis, the T<sub>TEX</sub> cooling is supportive of a change in depth of GDGT production or export in response to the onset of the EEP upwelling.

#### **Plio-Pleistocene [from 5.3 Ma] Interval.---**

The oxygen-isotope and temperature data indicate a long-term gradual thermocline shoaling and sea-surface cooling in the EEP (Fig. 4A, 4B) throughout this interval. In the WEP, the thermocline shoaled between 5.3 and 4 Ma, returning to a deep position between 4 and 1.8 Ma and shoaling again after 1.8 Ma. This interval is characterized by the initiation of a progressive asymmetry in the thermocline depth across the equatorial Pacific.

348 After 5.3 Ma, SSTs at IODP Site U1338 were warm ( $\sim 27^{\circ}\text{C}$ ), in agreement with a deep  
349 thermocline until 4.5 Ma (Fig. 4A). This result is supported by a rapid increase of  $T_{\text{TEX}}$  at  
350 U1338. Moreover, abundances of upwelling radiolarian species decreased again in the EEP  
351 (Kamikuri et al., 2009). In the WEP, the proto-warm pool period ended (Nathan and Leckie,  
352 2009). This interval coincides with the Messinian salinity crisis (Hilgen et al., 2007), during  
353 which the isolation of the Mediterranean Sea would have triggered a reduction of the North  
354 Atlantic Deep Water formation (NADW) at  $\sim 6$  Ma because of changing water density of the  
355 North Atlantic waters (Pérez-Asensio et al., 2012). According to model simulations, this  
356 process would result in a deepening of the thermocline in the equator and El Niño-like  
357 conditions (Rühlemann et al., 2004; Timmermann et al., 2005; Barreiro et al., 2008), thus  
358 providing a possible explanation to the results herein.

359 Numerous studies have focused on the magnitude of Pliocene equatorial Pacific warmth (4.5  
360 – 3.5 Ma) and the factors responsible for it (e.g., Raymo et al., 1996; Haywood and Valdes,  
361 2004; Ravelo et al., 2004; Barreiro et al., 2008; Rickaby and Halloran, 2005; Brierley et al.,  
362 2009; Scroxton et al., 2011; Ford et al., 2015). It is accepted that during the mid-Piacenzian  
363 Warm Period, persistent El-Niño like conditions prevailed. This interval, also known as El  
364 Padre mean state (Ford et al., 2015), is characterized by a deep and warm thermocline and  
365 warm surface conditions across the equatorial Pacific.

366 The low-resolution record presented here suggests a brief interval centered around 4 Ma when  
367 the thermocline deepened in the east and shoals in the west. SSTs in the EEP reach  $30^{\circ}\text{C}$  and  
368 around  $32^{\circ}\text{C}$  in the WEP (Fig. 4A, 4C,  $\text{Mg}/\text{Ca}_{G.\text{ruber}}$  SSTs; Medina-Elizalde et al., 2008).  
369 From 3.5 Ma, a pronounced zonal gradient of the thermocline depth and of the SSTs  
370 developed across the Pacific. The SST cooling trend and shoaling of the thermocline  
371 identified in the EEP coincides with the permanent establishment of the cold tongue  
372 (Groeneveld et al., 2006; Dekens et al., 2007; Steph et al., 2010; Rousselle et al., 2013). This



result is in agreement with Chaisson and Ravelo (2000) and Kamikuri et al., (2009), who report higher abundances of subsurface-dweller foraminifera and radiolarian upwelling species in the EEP at that time. Simultaneous with the changes in the EEP, the warm pool became established and the thermocline deepened in the WEP, as suggested by warmer surface waters and reduced  $\Delta T$  (Fig. 4C, Wara et al., 2005; Medina-Elizalde et al., 2008) and planktonic foraminifera abundances (Cannariato and Ravelo, 1997; Chaisson and Ravelo, 2000; Li et al., 2006). This La Niña-like pattern is consistent with earlier studies (Rickaby and Halloran 2005; Kamikuri et al., 2009; Steph et al., 2010; Ford et al., 2012 and Rousselle et al., 2013) in favor of an active equatorial upwelling and a strong Walker cell. Between 1.8 and 1.3 Ma, data indicate that the thermocline tilt and the SST gradient across the Pacific were reinforced (Fig. 4). This result is in agreement with the setting of the modern cold tongue identified by Martinez-Garcia et al. (2011).

#### *Evolution of the Pacific Mean State in a Regional and Global Context*

Prior research has attributed changes in the thermocline tilt to local tectonic events such as the opening and closing of the Panama and Indonesian oceanic gateways (e.g., LaRiviere et al., 2012), and changes in sea-surface-temperature zonal gradients to global climate perturbations or changes in regional wind patterns and strength (Hovan, 1995; Ford et al., 2012). However, there is still a strong debate about the timing of the closure of these oceanic gateways and their role in controlling the equatorial Pacific mean climate state. Montes et al., (2012, 2015), Osborne et al. (2014), and Sepulchre et al. (2014) suggested that the Central American Seaway was restricted by 10-11 Ma, which contradicts the commonly accepted late Pliocene timing of its closure (Keigwin, 1982; Duque-Caro, 1990; Haug and Tiedemann, 1998; Haug et al., 2001). On the other hand, Molnar and Cronin (2015) showed a marked restriction of the Indonesian Seaway from 5 Ma. This interpretation implies that the changes

of the equatorial Pacific mean state during the Miocene would have been controlled mainly by global climate changes.

The brief La Niña-like interval between 6.5 and 5.3 Ma may be attributable to the combination of the restricted flow through the Central American Seaway (Keigwin, 1982; Keller et al., 1989) and the 25 m sea-level drop at ~ 6.5 Ma (Haq et al., 1987; Hardenbol et al., 1998; Haq and Schutter, 2008) due to the expansion of ice sheets in Greenland (Larsen et al., 1994), Alaska (Bradshaw et al., 2012) and Antarctica (Billups, 2002; Williams et al. 2010) and the 2 Myr-long Northern Hemisphere glaciation (Larsen et al., 1994). This global cooling is thought to have contributed to the reinforcement of the equatorial upwelling and EUC.

Data from sediments younger than ~ 5 Ma indicate an important change in the equatorial Pacific mean state with the dominance of La Niña-like intervals. The onset of this long-term state coincides with a drastic restriction of the Indonesian Seaway (Srinivasan and Sinha, 1998; Molnar and Cronin, 2015), and changes in the global climate. The Indonesian Seaway restriction is thought to have contributed to the cooling of the eastern tropical Pacific over the last 5 Myr through the strengthening of the Walker circulation, leading to the increase in the Pacific zonal temperature gradient (Fig. 3, 4).

The La Niña-like event between 1.8 and 1.3 Ma coincides with pronounced ice growth in Antarctica (McKay et al., 2012) and the development of the northern-hemisphere ice sheets. The gradual increase of the pole-to-equator temperature gradient is thought to have reinforced the Walker cell, and affected the low-latitude zonal gradient (Molnar and Cane, 2002; McKay et al., 2012). Furthermore, modelling experiments show a positive feedback of the Pliocene low-latitude cooling on the global cooling (Fedorov et al., 2006). The shoaling of the thermocline increased the climate sensitivity of this area by strengthening the temperature gradient through the tropics and subsequently the Walker and Hadley cells (Brierley et al., 2009; Brierley and Fedorov, 2010). These processes led to the final setting of upwelling areas

(Philander and Fedorov, 2003; Dekens et al., 2007; Brierley et al., 2009; Brierley and Fedorov, 2010).

## CONCLUSION

This study demonstrates the complexity of reconstructing the evolution of the equatorial Pacific mean climate state and oceanographic features and the need of a multi-proxy approach to get a comprehensive understanding of the mechanism at play over the past 10 Myr. Combined isotopic zonal gradients between the surface (*Noelaerhabdaceae*) and subsurface (*G. menardii*) waters from the east and west equatorial Pacific reveals important steps towards the establishment of what is known today as El Niño–Southern Oscillation. The record suggests a general shoaling of the thermocline along the equator since the Late Miocene. The data show the appearance of the cold tongue at ~ 6.8 Ma before its proper establishment around 4.4 to 3.6 Ma (Chaisson 1995; Cannariato and Ravelo, 1997; Chaisson and Ravelo, 2000; Molnar and Cane, 2002; Ravelo et al., 2004, 2006; Sato et al., 2008; Steph et al., 2010; Rousselle et al., 2013) and its modern configuration ~ 1.8 Ma. This result is in agreement with the findings of LaRivière et al. (2012) and Zhang et al., (2014), who suggested progressive shoaling of the thermocline over the last 13 Myr.

The data indicate two critical transitions at about 5.3 Ma, when the thermocline globally started shoaling across the equatorial Pacific and around 3.8 Ma from an El-Niño-like-dominated mean state during the Late Miocene to a La-Niña-like-dominated state during the Plio-Pleistocene. These transitions coincide with marked regional and global changes. Locally, the restriction of the Indonesian Seaway and subsequent intensification of the Walker circulation increased the Pacific zonal temperature gradient over the last 5 Myr. From a global point of view, the growth of ice sheets in the northern hemisphere and in Antarctica most likely affected the Walker cell and the low-latitude zonal gradient.

447

## ACKNOWLEDGMENTS

448 We thank the European Consortium for Ocean Research Drilling (ECORD) for the ECORD  
449 Grant. We are also grateful to Anhelique Mets and Jort Ossebaar for support with the TEX<sub>86</sub>  
450 measurements. We finally want to thank Fabrice Minoletti for providing us the separation  
451 technique development necessary to then perform the isotopic measurements on  
452 *Noelaerhabdaceae* calcite. We also thank the Ocean and International Ocean drilling Program  
453 (ODP and IODP) for providing samples from Sites 806 and U1338. SS and AS were  
454 supported by the Netherlands Earth System Science Center funded by the Dutch Ministry  
455 Science and Education (OCW). MAS was supported by CNRS (Centre National de la  
456 Recherche Scientifique) for salary.

## REFERENCES

- Backman, J., Baldauf, J.G., Ciummelli, M., and Raffi, I., 2016, Data report: a revised biomagnetostratigraphic age model for Site U1338, IODP Expedition 320/321: Proceedings of the Integrated Ocean Drilling Program, 320/321, <http://doi.org/10.2204/iodp.proc.320321.219.2016>.
- Barreiro, M., Philander, G., Pacanowski, R., and Fedorov, A., 2005, Simulations of warm tropical conditions with application to middle Pliocene atmospheres: *Climate Dynamics*, v. 26, p. 349–365.
- Barreiro, M., Fedorov, A., Pacanowski, R., and Philander, S.G., 2008, Abrupt climate changes: how freshening of the Northern Atlantic affects the thermohaline and wind-driven oceanic circulations: *Annual Review of Earth and Planetary Sciences*, v. 36, p. 33-58.
- Beltran, C., Rousselle, G., Backman, J., Wade, B.S., and Sicre, M.A., 2014, Paleoenvironmental trigger for the development of bloom forming calcareous nannofossils: an example from the Late Miocene Eastern Equatorial Pacific: *Palaeoceanography*, v. 29 (3), p. 210-222.
- Billups, K., 2002, Late Miocene through early Pliocene deep water circulation and climate change viewed from the sub-Antarctic South Atlantic: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 185(3-4), p. 287-307.
- Boccaletti, G., Pacanowski, R.C., Philander, S.G.H., and Fedorov, A.V., 2004, The thermal structure of the upper ocean: *Journal of Physical Oceanography*, v. 34, p. 888–902
- Bradshaw, C.D., Lunt, D.J., Flecker, R., Salzmann, U., Pound, M.J., Haywood, A.M., and Eronen, J.T., 2012, The relative roles of CO<sub>2</sub> and palaeogeography in determining late Miocene climate: Results from a terrestrial model-data comparison: *Climate of the Past*, v. 8, p. 1257–1285.

482 Brassell, S.C., Eglinton, G., Marlowe, I.T., Pflaumann, U., and Sarnthein, M., 1986,  
 483 Molecular stratigraphy: a new tool for climatic assessment: *Nature*, v. 320, p. 129-133.

484 Brierley, C.M., and Fedorov, A.V., 2010, Relative importance of meridional and zonal sea  
 485 surface temperature gradients for the onset of the ice ages and Pliocene-Pleistocene  
 486 climate evolution: *Paleoceanography*, v. 25, PA2214, doi: 10.1029/2009PA001809.

487 Brierley, C., Fedorov, A.V., Liu, Z., Herbert, T.D., Lawrence, K.T., and LaRivière, J.P.,  
 488 2009, Greatly expanded tropical warm pool and weakened Hadley circulation in the  
 489 early Pliocene: *Science*, v. 323, p. 1714-1718.

490 Brzezinski, M.A., 1988, Vertical distribution of ammonium in stratified oligotrophic waters:  
 491 *Limnology and Oceanography*, v. 33, p. 1176-1182.

492 Cane, M.A., 1998, A role for the tropical Pacific: *Science*, v. 282(5386), p. 59-61, doi:  
 493 10.1126/science.282.5386.59.

494 Cannariato, K.G., and Ravelo, A.C., 1997, Pliocene-Pleistocene evolution of eastern tropical  
 495 Pacific surface water circulation and thermocline depth: *Paleoceanography*, v. 12(6),  
 496 p. 805-820.

497 Chaisson W.P., 1995, Planctonic foraminiferal assemblages and paleoceanographic change in  
 498 the trans-tropical Pacific Ocean: a comparison of West (leg 130) and East (leg 138),  
 499 latest Miocene to Pleistocene: *Proceedings of the Ocean Drilling Program, Scientific*  
 500 *Results*, v. 138, p. 555-581.

501 Chaisson, W.P., and Leckie, R.M., 1993, High-resolution Neogene planktonic foraminifer  
 502 biostratigraphy of Site 806, Ontong Java Plateau (western equatorial Pacific), *in*  
 503 Berger, W.H., Kroenke, L.W., Mayer, L.A., et al. eds., *Proceedings of Ocean Drilling*  
 504 *Program, Scientific Results*, 130, p. 137-178.

505 Chaisson, W.P., and Ravelo, A.C., 2000, Pliocene development of the east-west hydrographic  
 506 gradient in the equatorial Pacific: *Paleoceanography*, v. 15(5), p. 497-505.

507 Conte, M.H., Sicre, M-A., Rühlemann, C., Weber, J.C., Schulte, S., Schulz-Bull, D., and  
 508 Blanz, T., 2006, Global calibration of the alkenone unsaturation index ( $U^{K'}_{37}$ ) with  
 509 surface water production temperature and a comparison of the core top integrated  
 510 production temperatures recorded by  $U^{K'}_{37}$  with overlying sea surface temperatures:  
 511 *Geochemistry Geophysics Geosystems*, v. 7(2), p. 1-22.

512 Dekens, P.S., Ravelo, A.C., and McCarthy, M.D., 2007, Warm upwelling regions in the  
 513 Pliocene warm period: *Paleoceanography*, v. 22, p. 1-12.

514 Dekens, P.S., Ravelo, A.C., McCarthy, M.D., and Edwards, C.A., 2008, A 5 million year  
 515 comparison of Mg/Ca and alkenone paleothermometers: *Geochemistry, Geophysics,*  
 516 *Geosystems*, v. 9, doi:10.1029/2007GC001931.

517 Drury, A.J., Westerhold, T., Frederichs, T., Tian, J., Wilkens, R., Channell, J.E.T., Evans, H.,  
 518 John, C.M., Lyle, M., and Röhl, U., 2017, Late Miocene climate and time scale  
 519 reconciliation: Accurate orbital calibration from a deep-sea perspective: *Earth and*  
 520 *Planetary Science Letters*, v. 475, p. 254–266, doi:10.1016/j.epsl.2017.07.038.

521 Drury, A.J., Geoff, L., Gray, W.R., Lyle, M., Westerhold, T., Shevenell, A., and John, C.,  
 522 2018, Deciphering the State of the Late Miocene to Early Pliocene Equatorial  
 523 Pacific: *Paleoceanography and Paleoclimatology*, v. 33, doi:10.1002/2017PA003245.

524 Duque-Caro, H., 1990, Neogene stratigraphy, paleoceanography and paleobiogeography in  
 525 northwest South America and the evolution of the Panama Seaway: *Palaeogeography,*  
 526 *Palaeoclimatology, Palaeoecology*, v. 77, p. 203-234.

527 Farrell, J.W., Raffi, I., Janecek, T.R., Murray, D.W., Levitan, M., Dadey, K.A., Emeis, K.,  
 528 Lyle, M., Flores, J.-A., and Hovan, S., 1995, Late Neogene sedimentation patterns in  
 529 the eastern equatorial Pacific Ocean: *Proceedings of the Ocean Drilling Program,*  
 530 *Scientific Results*, v. 138, p. 717-756.

531 Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., DeMenocal, P.B., Barreiro, M., Pa  
 532 canowki, R.C., and Philander, S.G., 2006, The Pliocene paradox (mechanisms for a  
 533 permanent El Niño): *Science*, v. 312, p. 1485–1489.

534 Fedorov, A.V., Brierley, C.M., Lawrence, K.T., Liu, Z., Dekens, P.S., and Ravelo, A.,  
 535 2013, Patterns and mechanisms of early Pliocene warmth: *Nature*, v. 496, p. 43–49,  
 536 doi:10.1038/nature12003.

537 Ford, H.L., Ravelo, A.C., and Hovan, S., 2012, A deep Eastern Equatorial Pacific thermocline  
 538 during the early Pliocene warm period: *Earth and Planetary Science Letters*, v. 355-  
 539 356, p. 152-161.

540 Ford, H.L., Ravelo, A.C., Dekens, P.S., LaRiviere, J.P., and Wara, M.W., 2015, The  
 541 evolution of the equatorial thermocline and the early Pliocene El Padre mean state:  
 542 *Geophysical Research Letters*, v. 42, p. 4878–4887, doi:10.1002/ 2015GL064215.

543 Groeneveld, J., Steph, S., Tiedemann, R., Garbe, D., Nürnberg, D., and Sturn, A., 2006,  
 544 Pliocene mixed-layer oceanography for site 1241, using combined Mg/Ca and  $\delta^{18}\text{O}$   
 545 analyses of *Globigerinoides sacculifer*: *Proceedings of the Ocean Drilling Program*,  
 546 *Scientific Results*, v. 202, p. 1-27.

547 Haq, B.U., and Schutter, S.R., 2008, A chronology of Paleozoic sea-level changes: *Science*, v.  
 548 322(5898), p. 64-68.

549 Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the  
 550 Triassic (250 million years ago to present): *Science*, v. 235, p. 1156-1167.

551 Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.C., and Vail, P., 1998,  
 552 Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins,  
 553 in De Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R., and Farley, M.B., eds.,  
 554 Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: SEPM, Special  
 555 Publication 60, p. 3-13.



556 Haug, G.H., and Tiedemann, R., 1998, Effect of the formation of the Isthmus of Panama on  
557 Atlantic Ocean thermohaline circulation: *Nature*, v. 393, p. 673-676.

558 Haug, G.H., Tiedemann, R., Zahn, R., and Ravelo, A.C., 2001, Role of Panama uplift on  
559 oceanic freshwater balance: *Geology*, v. 29, p. 207-210.

560 Haywood, A.M, and Valdes, P.J., 2004, Modelling middle Pliocene warmth: contribution of  
561 atmosphere, oceans and cryosphere: *Earth and Planetary Science Letters*, v. 218, p.  
562 363–377.

563 Herbert, T.D., Lawrence, K.T., Tzanova, A., Peterson, L.C., Caballero-Gill, R., and Kelly,  
564 C.S., 2016, Late Miocene global cooling and the rise of modern ecosystems: *Nature*  
565 *Geoscience*, v. 9, p. 843–847, doi:10.1038/NGEO2813.

566 Hertzberg J.E., Schmidt M.W., Bianchi, T.S., Smith, R.W., Shields, M.R., and Marcantonio,  
567 F., 2016, Comparison of eastern tropical Pacific TEX<sub>86</sub> and *Globigerinoides ruber*  
568 Mg/Ca derived sea surface temperatures: Insights from the Holocene and Last Glacial  
569 Maximum: *Earth and Planetary Science Letters*, v. 434, p. 320-332.

570 Hilgen, F., Kuiper, K., Krijgsman, W., Snel, E., and Van Der Laan, E., 2007, Astronomical  
571 tuning as the basis for high resolution chronostratigraphy: the intricate history of the  
572 Messinian Salinity Crisis: *Stratigraphy*, v. 4(2-3), p. 231-238.

573 Hovan, S.A., 1995, Late Cenozoic atmospheric circulation intensity and climatic history  
574 recorded by eolian deposition in the eastern equatorial Pacific Ocean, Leg  
575 138: *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 138, p. 615–  
576 625.

577 Huguet, C., Schimmelmann, A., Thunell, R., Lourens, L.J., Sinninghe Damsté, J., and  
578 Schouten, S., 2007, A study of the TEX<sub>86</sub> paleothermometer in the water column and  
579 sediments of the Santa Barbara Basin, California: *Paleoceanography*, v. 22, p. 9.

580 Huguet, C., Martrat, B., Grimalt, J.O., Sinninghe Damsté, J.S., and Schouten, S., 2011,

581 Coherent millennial scale patterns in  $U^{K'}_{37}$  and  $TEX^{H}_{86}$  temperature records during the  
582 penultimate interglacial-to-glacial cycle in the western Mediterranean:  
583 *Paleoceanography*, v. 26, p. 10.

584 Kamikuri, S., Motoyama, I., Nishi, H., and Iwai, M., 2009, Evolution of Eastern Warm Pool  
585 and upwelling processes since the middle Miocene based on analysis of radiolarian  
586 assemblages: response to Indonesian and Central American Seaways: *Palaogeography*,  
587 *Palaeoclimatology, Palaeoecology*, v. 280, p. 469-479.

588 Karner, M.B., Delong, E.F., and Karl, D.M., 2001, Archaeal dominance in the mesopelagic  
589 zone of the Pacific Ocean: *Nature*, v. 409, p. 507–510.

590 Keigwin, L.D., 1982, Isotope paleoceanography of the Caribbean and east Pacific: Role of  
591 Panama uplift in late Neogene time: *Science*, v. 217, p. 350-353.

592 Keller, G., Zenker, C.E., and Stone, S.M., 1989, Late Neogene history of the Pacific -  
593 Caribbean gateway: *Journal of South American Earth Sciences*, v. 2(1), p. 73-108.

594 Kim, J.H., Schouten, S., Hopmans, E.C., Donner, B., and Sinninghe Damsté, J.S., 2008,  
595 Global sediment core-top calibration of the  $TEX^{H}_{86}$  paleothermometer in the ocean:  
596 *Geochimica et Cosmochimica Acta*, v. 72(4), p. 1154-1173.

597 Kim, J.H., Van Der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Koç, N.,  
598 Hopmans, E.C., and Sinninghe Damsté, J.S., 2010, New indices and calibrations  
599 derived from the distribution of crenarchaeal isoprenoid tetraether lipids: implications  
600 for past sea surface temperature reconstructions: *Geochimica et Cosmochimica Acta*,  
601 v. 74, p. 4639-4654.

602 Kim, J.H., Romero, O.E., Lohmann, G., Donner, B., Laepple, T., Haam, E., and Sinninghe  
603 Damsté, J.S., 2012, Pronounced subsurface cooling of North Atlantic waters off  
604 Northwest Africa during Dansgaard - Oeschger interstadials: *Earth and Planetary  
605 Science Letters*, v. 339-340, p. 95-102.

606 Könnike, M., Bernhard, A.E., De La Torre, J.R., Walker, C.B., Waterbury, J.B., and Stahl,  
 607 D.A., 2005, Isolation of an autotrophic ammonia-oxidizing marine  
 608 Archaeon: *Nature*, v. 437, p. 543–546.

609 Koutavas, A., Demenocal, G., Olive, C., and Lynch-Stieglitz, J., 2006, Mid-Holocene El Niño  
 610 - Southern Oscillation (ENSO) attenuation revealed by individual foraminifera in  
 611 eastern tropical Pacific sediments: *Geology*, v. 34, p. 993–996.

612 Kroenke, L.W., Berger, W.H., and Janecek, T.R., 1991, Site 806: Proceedings of the Ocean  
 613 Drilling Program, Initial reports, v. 130, p. 291-367.

614 LaRivière, J.P., Ravelo, A.C., Crimmins, A., Dekens, P.S., Ford, H.L., Lyle, M., and Wara,  
 615 M.W., 2012, Late Miocene decoupling of oceanic warmth and atmospheric carbon  
 616 dioxide forcing: *Nature*, v. 486, p. 97-100.

617 Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W., and Spezzaferri, S., 1994, Seven  
 618 million years of glaciation in Greenland: *Science*, v. 264, p. 952–955.

619 Lee, K.E., Kim, J.H., Wilke, I., Helmke, P., and Schouten, S., 2008, A study of the alkenone,  
 620 TEX<sub>86</sub>, and planktonic foraminifera in the Benguela Upwelling System: Implications  
 621 for past sea surface temperatures estimates: *Geochemistry, Geophysics, Geosystems*,  
 622 v. 9(10), p. 19.

623 Leider, A., Hinrichs, K.U., Mollenhauer, G., and Versteegh, G.J.M., 2010, Core-top  
 624 calibration of the lipid-based U<sup>K</sup><sub>37</sub> and TEX<sub>86</sub> temperature proxies on the southern  
 625 Italian shelf (SW Adriatic Sea, Gulf of Taranto): *Earth and Planetary Science Letters*,  
 626 v. 300(1-2), p. 112-124.

627 Li, Q., Li, B., Zhong, G., McGowran, B., Zhou, Z., Wang, J., and Wang, P., 2006, Late  
 628 Miocene development of the western Pacific warm pool: planktonic foraminifer and  
 629 oxygen isotopic evidence: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v.  
 630 237, p. 465-482.

631 Lopes Dos Santos, R.A., Prange, M., Castañeda, I.S., Schefuß, E., Mulitza, S., Schulz, M.,  
 632 Niedermeyer, E.M., Sinninghe Damsté, J.S., and Schouten, S., 2010, Glacial -  
 633 interglacial variability in Atlantic meridional overturning circulation and thermocline  
 634 adjustments in the tropical North Atlantic: *Earth and Planetary Science Letters*, v. 300,  
 635 p. 407-414.

636 Martin, R.E., 1999, Taphonomy and temporal resolution of foraminiferal assemblages, *in* Sen  
 637 Gupta, B.K., ed., *Modern Foraminifera*: Kluwer Academic Publishers, 371 p.

638 Martinez-Garcia, A., Rosell-Mele, A., Jaccard, S.L., Geibert, W., Sigman, D.M., and Haug,  
 639 G.H., 2011, Southern Ocean dust–climate coupling over the past four million years:  
 640 *Nature*, v. 476, p. 312-315, doi:10.1038/nature10310

641 McKay, R., Naish, T., Carter, L., Riesselman, C., Dunbar, R., Sjunneskog, C., Winter, D.,  
 642 Sangiorgi, F., Warren, C., Pagani, M., Schouten, S., Willmott, V., Levy, R., DeConto,  
 643 R., and Powell, R.D., 2012, Antarctic and Southern Ocean influences on Late Pliocene  
 644 global cooling: *National Academy of Sciences Proceedings (United States of*  
 645 *America)*, v. 109 (17), p. 6423-6428.

646 McPhaden, M.J., Zebiak, S.E., and Glantz, M.H., 2006, ENSO as an integrating concept in  
 647 *Earth science: Science*, v. 314, p. 1740–1745.

648 Medina-Elizalde, M., and Lea, D.W., 2010, Late Pliocene equatorial Pacific:  
 649 *Paleoceanography*, v. 25, PA2208, doi:10.1029/2009PA001780.

650 Medina-Elizalde, M., Lea, D.W., and Fantle, M.S., 2008, Implications of seawater Mg/Ca  
 651 variability for Plio-Pleistocene tropical climate reconstruction: *Earth and Planetary*  
 652 *Science Letters*, v. 269, p. 584–594.

653 Minoletti, F., Hermoso, M., and Gressier, V., 2009, Separation of sedimentary micron-sized  
 654 particles for palaeoceanography and calcareous nannoplankton biogeochemistry:  
 655 *Nature Protocols*, v. 4(1), p. 14 - 24.

656 Molnar, P., and Cane, M.A., 2002, El Niño's tropical climate and teleconnections as a  
657 blueprint for pre-Ice Age climate: *Paleoceanography*, v. 172, p. 1-13.

658 Molnar, P., and Cronin, T.W., 2015, Growth of the maritime continent and its possible  
659 contribution to recurring Ice Ages: *Paleoceanography*, v. 30, p. 196–225,  
660 doi:10.1002/2014PA002752.

661 Montes, C., Cardona, A., McFadden, R., Morón, S., Silva, J.C., Restrepo-Moreno, S.,  
662 Ramirez, D., Hoyos, N., Wilson, J. Farris, D., Bayona, G., Jaramillo, C., Valencia, V.,  
663 Bryan, J., and Flores, J.A., 2012, Evidence for middle Eocene and younger land  
664 emergence in Central Panama: Implications for Isthmus closure: *Geological Society of*  
665 *America, Bulletin*, v. 124, p. 780-799.

666 Montes, C., Cardona, A., Jaramillo, C., Pardo, A., Silva, J.C., Valencia, V., Ayala, C., Pérez-  
667 Angel, L.C., Rodríguez-Parra, L.A., Ramirez, V., and Niño, H., 2015, Middle  
668 Miocene closure of the Central American Seaway: *Science*, v. 348, p. 226-229, doi:  
669 10.1126/science.aaa2815.

670 Mudelsee, M., and Raymo, M.E., 2005, Slow dynamics of the Northern Hemisphere  
671 glaciation: *Paleoceanography*, v. 20, PA4022, doi:10.1029/2005PA001153.

672 Murray, A.E., Blakis, A., Massana, R., Strawzewski, S., Passow, U., Alldredge, A., and  
673 Delong, E.F., 1999, A time series assessment of planktonic archaeal variability in the  
674 Santa Barbara Channel: *Aquatic Microbial Ecology*, v. 20, p. 129–145.

675 Nathan, S.A., and Leckie, R.M., 2009, Early history of the Western Pacific Warm Pool during  
676 the middle to late Miocene (~13,2-5,8 Ma): Role of sea-level change and implications  
677 for equatorial circulation: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 274,  
678 p. 140-159.

679 Neelin, J.D., Battisti, D.S., Hirst, A.C., Jin, F.-F., Wakata, Y., Yamagata, T., and Zebiak,  
680 S.E., 1998, ENSO Theory: *Journal of Geophysics Research*, v. 103, p. 14,261–14,290.

681 Osborne, A.H., Newkirk, D.R., Groeneveld, J., Martin, E.E., Tiedemann, R., and Frank, M.,  
 682 2014, The seawater neodymium and lead isotope record of the final stages of Central  
 683 American Seaway closure: *Paleoceanography*, v. 29(7), p. 715–729,  
 684 doi:10.1002/2014PA002676.

685 Pagani, M., Liu, Z., LaRiviere, J., and Ravelo, A.C., 2010, High Earth-system climate  
 686 sensitivity determined from Pliocene carbon dioxide concentrations: *Nature*  
 687 *Geoscience*, v. 3, p. 27-30.

688 Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and the Expedition 320/321  
 689 Scientists, 2010, Site 1338: Proceedings of the International Ocean Drilling Program  
 690 320/321, Expedition Reports, v. 321, 141 p.

691 Pälike, H., Lyle, M.W., Nishi, H., Raffi, I., Ridgwell, A., Gamage, K., Klaus, A., Acton, G.,  
 692 Anderson, L., Backman, J., Baldauf, J., Beltran, C., Bohaty, S.M., Bown, P., Busch,  
 693 W., Channell, J.E., Chun, C.O., Delaney, M., Dewangan, P., Dunkley Jones, T.,  
 694 Edgar, K.M., Evans, H., Fitch, P., Foster, G.L., Gussone, N., Hasegawa, H., Hathorne,  
 695 E.C., Hayashi, H., Herrle, J.O., Holbourn, A., Hovan, S., Hyeong, K., Iijima, K., Ito,  
 696 T., Kamikuri, S., Kimoto, K., Kuroda, J., Leon-Rodriguez, L., Malinverno, A., Moore,  
 697 T.C.J.R., Murphy, B.H., Murphy, D.P., Nakamura, H., Ogane, K., Ohneiser, C.,  
 698 Richter, C., Robinson, R., Rohling, E.J., Romero, O., Sawada, K., Scher, H.,  
 699 Schneider, L., Sluijs, A., Takata, H., Tian, J., Tsujimoto, A., Wade, B.S., Westerhold,  
 700 T., Wilkens, R., Williams, T., Wilson, P.A., Yamamoto, Y., Yamamoto, S., Yamazaki,  
 701 T., and Zeebe, R.E., 2012, A Cenozoic record of the equatorial Pacific carbonate  
 702 compensation depth: *Nature*, v. 488(7413), p. 609–614, doi:10.1038/nature11360.

703 Pearson, P.N., Van Dongen, B.E., Nicholas, C.J., Pancost, R.D., Schouten, S., Singano, J.M.,  
 704 and Wade, B.S., 2007, Stable warm tropical climate through the Eocene epoch:  
 705 *Geology*, v. 35(3), p. 211-214.

706 Pérez-Asensio, J.N., Schmiedl, G., Aguirre, J., and Civis, J., 2012, Impact of restriction of the  
 707 Atlantic-Mediterranean gateway on the Mediterranean Outflow Water and eastern  
 708 Atlantic circulation during the Messinian: *Paleoceanography*, v. 27 (3), PA3222,  
 709 doi:10.1029/2012PA002309.

710 Philander, S., and Fedorov, A., 2003, Role of tropics in changing the response to Milankovich  
 711 forcing some three million years ago: *Paleoceanography*, v. 18,  
 712 doi:10.1029/2002PA000837.

713 Pisias, N.G., Mayer, L.A., Janecek, T.R., Palmer-Julson, A., and Van Andel, T.H., 1995,  
 714 Proceedings of the Ocean Drilling Program, Scientific results, v. 138.

715 Prah, F.G., Muehlhausen, L.A., and Zahnle, D.L., 1988, Further evaluation of long-chain  
 716 alkenones as indicators of paleoceanographic conditions: *Geochimica et*  
 717 *Cosmochimica Acta*, v. 52, p. 2303–2310.

718 Ravelo, A.C., and Fairbanks, R.G., 1992, Oxygen isotopic composition of multiple species of  
 719 planktonic foraminifera: recorders of the modern photic zone temperature gradient:  
 720 *Paleoceanography*, v. 7, p. 815-831.

721 Ravelo, A.C., and Shackleton, N.J., 1995, Evidence for surface-water circulation changes at  
 722 Site 851 in the eastern tropical Pacific Ocean: Proceedings of the Ocean Drilling  
 723 Program, Scientific Results, v. 138, p. 503-514.

724 Ravelo, A.C., Andreasen, D., Lyle, M., Olivarez, L., and Wara, M.W., 2004, Regional climate  
 725 shifts caused by gradual global cooling in the Pliocene Epoch: *Nature*, v. 429, p. 263-  
 726 267.

727 Ravelo, A.C., Dekens, P.S., and McCarthy, M., 2006, Evidence for El Niño-like conditions  
 728 during the Pliocene: *Geological Society of America Today*, v. 16(3), p. 4-11.

729 Raymo, M.E., Grant, B., Horowitz, M., and Rau, G.H., 1996, Mid-Pliocene warmth: stronger  
 730 greenhouse and stronger conveyor: *Marine Micropaleontology*, v. 27, p. 313-  
 731 326, doi:10.1016/0377-8398(95)00048-8.

732 Rickaby, R.E.M., and Halloran, P., 2005, Cool La Niña the warmth of the Pliocene: *Science*,  
 733 v. 307, p. 1948-1952.

734 Rommerskirchen, F., Condon, T., Mollenhauer, G., Dupont, L., and Schefuss, E., 2011,  
 735 Miocene to Pliocene development of surface and subsurface temperatures in the  
 736 Benguela Current system: *Paleoceanography*, v. 26, 15 p.

737 Roth, P.H., 1986, Mesozoic paleoceanography of the North Atlantic and Tethys Oceans,  
 738 North Atlantic: *Paleoceanography*, v. 21, p. 299-320.

739 Rousselle, G., Beltran, C., Sicre, M.-A., Raffi, I., and De Rafélis, M., 2013, Sea-surface  
 740 condition changes in the Equatorial pacific during the Mio-Pliocene as inferred from  
 741 coccoliths geochemistry: *Earth and Planetary Science Letters*, v. 361, p. 412-421.

742 Rühlemann, C., Mulitza, S., Lohmann, G., Paul, A., Prange, M., and Wefer, G., 2004,  
 743 Intermediate depth warming in the tropical Atlantic related to weakened thermohaline  
 744 circulation: Combining paleoclimate data and modelling results for the last  
 745 deglaciation: *Paleoceanography*, v. 19, 10 p.

746 Sato, K., Oda, M., Chiyonobu, S., Kimoto, K., Domitsu, H., and Ingle, J.C., 2008,  
 747 Establishment of the western Pacific warm pool during the Pliocene: Evidence from  
 748 planktic foraminifera, oxygen isotopes, and Mg/Ca ratios: *Palaeogeography*,  
 749 *Palaeoclimatology*, *Palaeoecology*, v. 265, p. 140-147.

750 Schneider, B., and Schmittner, A., 2006, Simulating the impact of the Panamanian seaway  
 751 closure on ocean circulation, marine productivity and nutrient cycling: *Earth and*  
 752 *Planetary Science Letters*, v. 246, p. 367-380.



753 Schouten, S., Hopmans, E.C., Schefuss, E., and Sinninghe Damsté, J.S., 2002, Distributional  
 754 variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing  
 755 ancient sea water temperatures?: *Earth and Planetary Science Letters*, v. 204, p. 265-  
 756 274.

757 Schouten, S., Huguet, C., Hopmans, E.C., Kienhuis, M.V.M., and Sinninghe Damsté, J.S.,  
 758 2007, Improved analytical methodology and constraints on analysis of the TEX<sub>86</sub>  
 759 paleothermometer by high performance liquid chromatography/atmospheric pressure  
 760 chemical ionization-mass spectrometry: *Analytical Chemistry*, v. 79, p. 2940-2944.

761 Schouten, S., Hopmans, E.C., and Sinninghe Damsté, J.S., 2013, The organic geochemistry of  
 762 glycerol dialkyl glycerol tetraether lipids: a review: *Organic geochemistry*, v. 54, p.  
 763 19-61.

764 Scroxton, N., Bonham, S.G., Rickaby, R.E.M., Lawrence, S.H.F., Hermoso, M., and  
 765 Haywood, A.M., 2011, Persistent El Niño–Southern Oscillation variation during the  
 766 Pliocene Epoch: *Paleoceanography*, v. 26, PA2215, doi:10.1029/2010PA002097.

767 Seki, O., Foster, G.L., Schmidt D.N., Mackensen, A., Kawamura, K., and Pancost, R.D.,  
 768 2010, Alkenone and boron-based Pliocene pCO<sub>2</sub> records: *Earth and Planetary Science*  
 769 *Letters*, v. 292, p. 201-211, doi:10.1016/j.epsl.2010.01.037.

770 Seki, O., Schmidt, D.N., Schouten, S., Hopmans, E.C, Sinninghe Damsté, J.S., and Pancost,  
 771 R.D., 2012, Paleoceanographic changes in the Eastern Equatorial Pacific over the last  
 772 10 Myr: *Paleoceanography*, v. 27, PA3224, doi:10.1029/2011PA002158.

773 Sepulchre, P., Arsouze, T., Donnadieu, Y., Dutay, J.C., Jaramillo, C., Le Bras, J., Martin, E.,  
 774 Montes, C., and Waite, A., 2014, Consequences of shoaling of the Central American  
 775 Seaway determined from modeling Nd isotopes: *Paleoceanography*, v. 29, p. 176-189,  
 776 doi:10.1002/2013PA002501.

777 Sinninghe Damsté, J.S., Hopmans, E.C., Schouten, S., Van Duin, A.C.T., and Geenevasen,  
 778 J.A.J., 2002, Crenarchaeol: the characteristic core glycerol dibiphytanyl glycerol  
 779 tetraether membrane lipid of cosmopolitan pelagic crenarchaeota: *Journal of Lipid*  
 780 *Research*, v. 43, p. 1641–1651.

781 Spero, H.J., Mielke, K.M., Kalve, E.M., Lea, D.W., and Pak, D.K., 2003, Multispecies  
 782 approach to reconstructing eastern equatorial Pacific thermocline hydrography during  
 783 the past 360 kyr: *Paleoceanography*, v. 18(1), p. 1-16.

784 Srinivasan, M.S., and Sinha, D.K., 1998, Early Pliocene closing of the Indonesian Seaway:  
 785 evidence from north-east Indian Ocean and Tropical Pacific deep sea cores: *Journal of*  
 786 *Asian Earth Sciences*, v. 16(1), p. 29-44.

787 Steph, S., Tiedemann, R., Prange, M., Groeneveld, J., Schulz, M., Timmermann, A.,  
 788 Nürnberg, D., Rühlemann, C., Saukel, C., and Haug, G.H., 2010, Early Pliocene  
 789 increase in thermohaline overturning: A precondition for the development of the  
 790 modern equatorial Pacific cold tongue: *Paleoceanography*, v. 25, 17 p.

791 Takayama, T., 1993, Notes on Neogene calcareous nannofossil biostratigraphy of the Ontong  
 792 Java Plateau and size variations of *Reticulofenestra* coccoliths, *in* Berger, W.H.,  
 793 Kroenke, L.W., Mayer, L.A., et al. eds., *Proceedings of the Ocean Drilling Program:*  
 794 *Scientific Results*, v. 130, p. 179–229.

795 Ternois, Y., Sicre, M.-A., and Paterne, M., 2000, Climatic changes along the northwestern  
 796 African continental margin over the last 30 kyrs: *Geophysical Research Letters*, v.  
 797 27(1), p. 133-136.

798 Tian, B., Zhang, G.J., and Ramanathan, V., 2001, Heat balance in the Pacific warm pool  
 799 atmosphere during TOGA COARE and CEPEX: *Journal of Climate*, v. 14(8), p.  
 800 1881–1893.

801 Tierney, J.E., and Tingley, M.P., 2015, A TEX<sub>86</sub> surface sediment database and extended  
 802 Bayesian calibration: Scientific Data, 2150029, doi: 10.1038/sdata.2015.29.  
 803 Tierney, J.E., and Tingley, M.P., 2018, BAYSPLINE: A new calibration for the alkenone  
 804 paleothermometer: Paleoclimatology and Paleoclimatology, v. 33, p. 281–301,  
 805 doi:10.1002/2017PA003201.  
 806 Timmermann, A., An, S.I., Krebs, U., and Goosse, H., 2005, ENSO Suppression due to  
 807 weakening of the North Atlantic thermohaline circulation: Journal of Climate, v. 18, p.  
 808 3122-3139.  
 809 Wakeham, S.G., Peterson, M.L., Hedges, J.I., and Lee, C., 2002, Lipid biomarker fluxes in  
 810 the Arabian Sea, with a comparison to the equatorial Pacific Ocean: Deep-Sea  
 811 Research II, v. 49, p. 2265–2301.  
 812 Wakeham, S.G., Hopmans, E.C., Schouten, S., and Sinninghe Damsté J.S., 2004, Archaeal  
 813 lipids and anaerobic oxidation of methane in euxinic water columns: A comparative  
 814 study of the Black Sea and Cariaco Basin: Chemical Geology, v. 205, p. 427-442.  
 815 Wara, M.W., Ravelo, A.C., and Delaney, M.L., 2005, Permanent El Niño-Like Conditions  
 816 During the Pliocene Warm Period: Science, v. 309, p. 758-761.  
 817 Williams, T., Van De Flierdt, T., Hemming, S.R., Chung, E., Roy, M., and Goldstein, S.L.,  
 818 2010, Evidence for iceberg armadas from East Antarctica in the Southern Ocean  
 819 during the late Miocene and early Pliocene: Earth and Planetary Science Letters, v.  
 820 290, p. 351–361.  
 821 Woodruff, F., and Savin, S.M., 1989, Miocene deep water oceanography: Paleoclimatology,  
 822 v. 4(1), p. 87-140.  
 823 Wuchter, C., Schouten, S., Wakeham, S.G., and Sinninghe Damsté, J.S., 2005, Temporal and  
 824 spatial variation in tetraether membrane lipids of marine Crenarchaeota in particulate

825 organic matter: Implications for TEX<sub>86</sub> paleothermometry: *Paleoceanography*, v. 20,  
826 PA3013, doi:10.1029/2004PA001110.

827 Yin, J.H., and Battisti, D. S., 2001, The importance of tropical sea surface temperature  
828 patterns in simulations of Last Glacial Maximum climate: *Journal of Climate*, v. 14, p.  
829 565–581.

830 Zhang, Y.G., Pagani, M., and Liu, Z., 2014, A 12-million-year temperature history of the  
831 tropical Pacific Ocean: *Science*, v. 344, p. 84-86.

832

## FIGURE CAPTIONS

**Figure 1. A)** Modern equatorial Pacific sea-surface temperatures (SSTs) from Ocean Data View. The white dots show the location of the study sites, ODP 806 and IODP U1338. The gray dots indicate the sites of previously published oxygen-isotope records (ODP 847 and 1241). WPWP, Western Pacific Warm Pool; EPWP, Eastern Pacific Warm Pool; NEC, North Equatorial Current; SEC, South Equatorial Current; EUC, Equatorial Under Current; NECC, North Equatorial Counter Current, PC, Peru Current (modified after Pisias et al., 1995). **B)** Cross sections of temperature (colors) and currents (vectors) averaged over 2.5°S-2.5°N (modified after US CLIVAR).

**Figure 2.** Comparison of El Niño-like (in red) and La Niña-like (in blue) time periods inferred from previous studies using different proxies from the EEP and WEP over the past 12 Myrs.

**Figure 3. A)**  $\delta^{18}\text{O}$  records in the EEP.  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  at IODP Site U1338 from Rousselle et al. (2013),  $\delta^{18}\text{O}_{G. \text{sacculifer}}$  and  $\delta^{18}\text{O}_{G. \text{tumida}}$  at site 847 from Wara et al. (2005),  $\delta^{18}\text{O}_{G. \text{menardii}}$  at Site U1338. **B)**  $\delta^{18}\text{O}$  records in the WEP.  $\delta^{18}\text{O}_{\text{Noelaerhabdaceae}}$  and  $\delta^{18}\text{O}_{G. \text{menardii}}$  at ODP Site 806.

**Figure 4. A)** Temperature records at IODP Site U1338 (EEP):  $\text{U}^{\text{K}'}_{37}$ -derived SST and  $\text{TEX}_{86}$ -derived temperatures. The shaded areas represent the error bars of the temperature estimates (light blue:  $\text{TEX}_{86}$ -derived temperatures and dark blue:  $\text{U}^{\text{K}'}_{37}$ -derived SST). The arrows (black and blue) highlight the temperature trends. **B)** Isotopic gradient ( $\Delta\delta^{18}\text{O}$ ) between surface and thermocline waters at IODP site U1338 (EEP) and ODP Site 806 (WEP). The evolution of the thermocline depth in the EEP and the WEP over the last 10 Ma according to the  $\Delta\delta^{18}\text{O}$  is also

858 shown. C) Temperature records at ODP Site 806:  $U^{K'}_{37}$ -derived SST (Pagani et al., 2010) in  
859 green,  $TEX_{86}$ -derived temperatures (Zhang et al., 2014) in red,  $Mg/Ca_{G.ruber}$ -derived SST  
860 (Medina-Elizalde et al., 2008) in brown and  $Mg/Ca_{G.tumida}$ -derived temperature (Ford et al.,  
861 2015) in orange.