Evolution of the Oligotrophic West Pacific Warm Pool During the Pliocene-Pleistocene Boundary

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Abstract This study investigates the development of oligotrophic conditions, thickening, and zonal and meridional contraction of the West Pacific Warm Pool (WPWP) during the Pliocene. It has been hypothesized that the evolution of the WPWP and the establishment of strong equatorial Pacific zonal gradients are closely related to the narrowing of the Indonesian Gateway (IG) as well as the closure of the Central American Seaway (CAS). However, the timing of the development of these events remains unclear. Here we report Pliocene-to-Recent relative abundances of planktic foraminifera from both sites indicates a pronounced increase in their population between ~3.15 and 1.6 Ma. There is a contemporaneous decrease in the Globigerinita glutinata population during this time, which together with the MSL data suggest the development of oligotrophic conditions in the western tropical Pacific. Our data suggest that the oligotrophic WPWP, resembling present-day conditions, developed around 3.15 Ma and was closely linked to the gradual constriction of the IG.

1. Introduction

The West Pacific Warm Pool (WPWP) encompasses a large swath (>30 x 10^6 km^2) of the tropical-subtropical western Pacific Ocean (Cane & Molnar, 2001) and is characterized by warm surface waters with an annual sea surface temperature (SST) of >28°C (Webster & Palmer, 1997; Yan et al., 1992) (Figure 1). The WPWP is ~2–5°C warmer than any other equatorial region and stores substantial amounts of heat (Yan et al., 1992). As a result, changes in the size, temperature, and position of the WPWP affect poleward heat transport from the equator and play an important role in the evolution of the El Niño-Southern Oscillation (ENSO) events (De Garidel-Thornton et al., 2005; Meyers, 1996; Sun, 2003). Easterly trade winds keep the WPWP toward the western equatorial Pacific (WEP) under normal conditions (Li et al., 2006), although its position fluctuates during ENSO events. A weakened Walker circulation is expected to replicate a more eastward expansion of warm pool or “El Niño-like” conditions in the tropical Pacific (Vecchi & Soden, 2007). A strong Hadley cell (HC) has also been associated with the meridional contraction of WPWP toward the equator, and a weak HC is responsible for the expanded WPWP (Brierley et al., 2009; Jia et al., 2008).

Oceanographically, the WPWP is composed of a thick and warm mixed layer and deep thermocline (~200 m). In contrast, the eastern equatorial Pacific (EEP) has a small mixed layer and a more shallow thermocline (Figure 2), resulting in the EEP being more productive than the WEP (Ravelo et al., 2006). About 10–15 Sv (1 Sv = 10^6 m^3 s^-1) of low-salinity, warm water enters the eastern Indian ocean from the WPWP annually (Chong et al., 2000; Ganachaud & Wunsch, 2000) and is termed the Indonesian Throughflow (ITF). The ITF transports heat from the WEP north of the equator to 12°S into the eastern Indian Ocean, mostly through the Makassar Strait (Gordon et al., 1999), and varies on annual, interannual, and (multi) decadal timescales according to observations (Linsley et al., 2010). Variability in the ITF influences global climates on both short- (ENSO-related) and long-term timescales, including tectonic timescales (Cane & Molnar, 2001; Gordon et al., 2003; Kuhl et al., 2004). Observations suggest that fluctuations in ENSO and related changes in the Indian monsoon system are linked to major influxes of Pacific freshwater and heat into the Indian Ocean (Vranes et al., 2002), wherein the ITF transport is greater during La Niña events as compared to El Niño events. (Gordon & Fine, 1996).
2. Evolution of the WPWP

Small changes in the dimensions of oceanic gateways can influence ocean circulation and heat distribution and may therefore have a profound impact on global climate as well as ocean productivity (Cane & Molnar, 2001; Nathan & Leckie, 2009). Numerous studies have hypothesized that the Miocene to Pliocene constriction of the Indonesian Gateway (IG), the closure of the Central American Seaway (CAS), and the development of the WPWP are closely linked (Chaisson & Ravelo, 2000; Jian et al., 2006; Keller, 1985; Kennett et al., 1985; Li et al., 2006; Nathan & Leckie, 2009). For instance, the progressive narrowing of the IG is purported to have played a key role in altering and redirecting ocean currents and causing climate change in the tropical eastern Indian and western Pacific Oceans. Despite significant progress regarding the constriction of the IG, closure of the CAS, and evolution of the WPWP, the timing of the tectonic constriction of these vital gateways still remains debated, with estimates of age ranging from ~17 to 3 Ma. For example, Cane and Molnar (2001) suggested that the northward movement of New Guinea during the Pliocene and subsequent constriction of the IG prevented the transport of warm, saline South Pacific waters into the Indian Ocean and key to the establishment of the WPWP. However, planktic foraminifera records from the WEP and South China Sea (SCS) suggest development and intensification of the WPWP ~10–11 Ma. The IG influences conditions in the EEP via the Equatorial
Undercurrent (EUC) (Keller, 1985; Kennett et al., 1985). The EUC gradually shoaled in the EEP during the past 10 Myr, likely due to narrowing of the IG (Keller, 1985; Kennett et al., 1985) and the subsequent closure of the CAS (Sepulchre et al., 2014). CAS closure played a key role in the Pliocene shoaling of the equatorial Pacific thermocline (Ford et al., 2012, 2015; Steph et al., 2010; Zhang et al., 2012). For instance, Chaisson and Ravelo (2000) used planktic foraminiferal abundances and multispecies stable isotopic data from the WEP and EEP, suggesting that the east-west thermocline tilt developed in the equatorial Pacific during 4.5 to 4 Ma and was related to the closure of the CAS. Results based on multispecies foraminiferal isotopic analyses and assemblages of equatorial Pacific deep sea cores suggest the evolution of the modern WPWP after ~3.6–3.0 Ma (Cannariato & Ravelo, 1997; Chaisson, 1995; Chaisson & Ravelo, 2000; Ravelo et al., 2006; Sato et al., 2008).

Here we present a 5 Myr record of planktic foraminiferal abundances from Ocean Drilling Program (ODP) Site 807 and Deep Sea Drilling Project (DSDP) Site 214 to constrain the evolution of the WPWP over the Pliocene–Pleistocene boundary. We compare our results with previous records from the WEP (ODP Site 806 and DSDP Site 586), EEP (ODP Sites 846, 847, 849, and 850), SCS (ODP Sites 1143 and 1147/1148), and a site offshore of eastern New Zealand (ODP Site 1125, north slope of Chatham Rise) to explore the spatiotemporal variability of regional paleoceanography. Finally, we discuss the implications of our data set and analyses to the timing of the evolution of the oligotrophic WPWP under the influence constricting IG and SST-induced intensified atmospheric circulations. All the sites are plotted in Figure 1 for reference.

3. Materials and Methods

3.1. Materials

Samples are from ODP Site 807, located in the western Pacific (latitude 3°36.42′N, longitude 156°37.49′, water depth 2,803.8 m below sea level [mbsl], which is located in the western Pacific; Kroenke et al., 1991). The age model used for Site 807 is adopted from the Scientific Reports of ODP Leg 130 (Berggren, Hilgen, et al., 1995, Berggren, Kent, et al., 1995) based on nannofossil and foraminiferal datums. Age control points are presented in supporting information Table S1 and have been updated following the recent geological timescale (Gradstein et al., 2012) (Figure 3a). Samples were analyzed for mixed-layer species (MLS) with a resolution of ~19 Kyr per sample.

DSDP Site 214 is located in the eastern Indian Ocean (latitude 11°20.2′S, longitude 88°43.08′E, water depth 1,671 mbsl) (von der Borch et al., 1974). Samples were analyzed for MLS with a resolution of ~18 Kyr per sample. The age model used for Site 214 is based on nannofossil and foraminiferal datums. Age control points are presented in supporting information Table S2 and have been updated following the recent geological timescale (Gradstein et al., 2012) (Figure 3a). Samples were analyzed for mixed-layer species (MLS) with a resolution of ~19 Kyr per sample.

Samples from Site 807 and 214 are well above the present-day lysocline depth. At Site 807 the lysocline depth is 3,300 m (Berger & Killingley, 1982) and at Site 214 the lysocline depth lies at about 3,800–4,000 m (Kolla et al., 1976). All samples were washed over a 63 μm sieve, following the method of Gupta and Thomas (1999, 2003). Contamination was avoided by staining the sieve with methylene blue solution after each wash so that residual microfossils were easily identified and removed.

Figure 3. Depth versus Age plot at (a) Sites 807 and b 214 based on foraminiferal and nannofossil datums (Gradstein et al., 2012). T = Top/LAD; B = Base/FAD. LAD = Last Appearance Datum; FAD = First Appearance Datum.
Sample processing was carried out in the Sample Processing Unit of the Paleoceanography and Paleoclimatology Laboratory, Department of Geology and Geophysics, IIT Kharagpur.

3.2. Methods
3.2.1. Planktic Foraminifera Census Counts
To investigate changes in oligotrophic conditions at the study sites, five MLS of planktic foraminifera were selected for census counts of relative population abundances. These species included *Trilobatus sacculifer* (formerly *Globigerinoides*; Spezzaferri et al., 2015), *Globigerinoides ruber*, *Globigerinita glutinata*, *Globigerinoides extremus*, *Globigerinoidesella fistulosa*, and *Globigerinoides obliquus*. We followed the work of Kennett and Srinivasan (1983) and Parker (1962) for taxonomy and identification of planktic foraminifera.

Two hundred seventy one (271) samples from Site 807 (western Pacific) and 267 samples from DSDP Site 214 (eastern Indian Ocean) were analyzed. The dried >149 μm size fraction was split into suitable aliquots to obtain approximately 300 specimens of planktic foraminifera which were then identified and counted as percentages of overall species (following den Dulk et al., 1998; Gupta & Thomas, 2003; Gupta et al., 2004). We chose the aforementioned species to investigate oligotrophic conditions in the WPWP with the following rationale.

*Globigerinita glutinata* has a wide latitudinal occurrence and can tolerate a rather wide range of temperature from 14°C to 30°C and 34.4 to 36.4 psu salinities (Bé & Hutson, 1977) and is moderately vulnerable to dissolution. *Globigerinita glutinata* is also known to be found in high abundances in the middle-to-high latitudes as well as in marginal upwelling areas in the low latitudes (Fairbanks et al., 1982; Kawahata et al., 2002; Pfaumann & Jian, 1999; Thunell & Reynolds, 1984). However, the distribution of *G. glutinata* is mainly linked to changes in paleoproductivity (Crundwell et al., 2008) and can thus be used to assess the onset of oligotrophic conditions in the WPWP.

*Globigerinoides ruber* is a tropical-subtropical, thermophilic, mixed-layer oligotrophic warm species, occurring over a surface temperature range of 14°C to 30°C. They are highly abundant between 21°C and 29°C and across a range of salinities (Bé, 1977; Bé & Tolderlund, 1971). *Globigerinoides ruber* is found in the mixed layer throughout the year (Farmer et al., 2007; Thirumalai et al., 2014).

*Trilobatus sacculifer*, *G. extremus*, and *G. obliquus* are tropical, mixed-layer, shallow-dwelling species preferring temperatures >24°C and low seasonal changes in SST as well as vertical temperature gradients. These species cannot tolerate large seasonal salinity changes and are vulnerable to dissolution (Bé, 1977; Cannariato & Ravelo, 1997; Fairbanks et al., 1982; Patrick & Thunell, 1997; Pfaumann & Jian, 1999; Thunell & Reynolds, 1984). *Trilobatus sacculifer* has preference for temperatures between 24°C and 30°C (Bé & Hutson, 1977; Bé & Tolderlund, 1971) and is most abundant in low nutrient oligotrophic environments (Bijma et al., 1990).

*Globigerinoidesella fistulosa* is a tropical to warm-subtropical, open-ocean, MLS with symbionts (Aze et al., 2011; Kennett & Srinivasan, 1983). This species has been distinguished recently from its ancestor, the *T. sacculifer* plexus, based on morphological study and, in particular, the presence of elongate protuberances in the final chambers (Poole & Wade, 2019).

4. Results
Census data for MLS abundances from Site 807 and Site 214 show a similar trend from 5 to 1.6 Ma (Figure 4), with a strong positive correlation (Figure 4.1) \( (R = 0.8218; p \text{ value} < 0.0001) \) between both data sets during 5 to 1.6 Ma. The average MLS population abundance from 5 to 4 Ma is 3.8% \( (1\sigma = \pm 1.33) \) at Site 807 and 3.27% \( (1\sigma = \pm 1.06) \) at Site 214. From 4 to ~3.15 Ma the MLS population abundances at both sites show a gradual increase in their population with an average of 5.4% \( (1\sigma = \pm 2.0) \) at Site 807 and 4.00% \( (1\sigma = \pm 1.48) \) at Site 214. Thereafter, data from both sites show a significant increase in their MLS population between ~3.15 and 1.9 Ma, with an average population abundance of 15.9% \( (1\sigma = \pm 5.71) \) at Site 807 and 18.38% \( (1\sigma = \pm 9.37) \) at Site 214 (Figure 4.2 and supporting information Table S3). In contrast to the MLS abundances, *G. glutinata*, an open-ocean paleoproductivity indicator species (Crundwell et al., 2008), shows a drop in its population at Site 807 starting at ~3.15 Ma (maximum value 5.46%) and persistently decreases up to ~1.6 Ma (minimum value 0.00%), (Figure 4).
5. Discussion

5.1. Deepening Mixed Layer of the WPWP

Our data reveal pronounced changes in the surface ocean which occurred across the Pliocene-Pleistocene boundary. We observe a noticeable increase in MLS abundances beginning at ~3.15 Ma at both sites. 

**Figure 4.** (a) Percentage distribution of *Globigerinita glutinata*, (b) % mixed layer species at ODP Site 807 (orange) and DSDP Site 214 (blue). Thick lines are 10 pts running average. Arrows are indicating oligotrophic conditions and thickening of the West Pacific Warm Pool. Figure 4.1. Statistical correlation of relative abundances of MLS at Sites 807A and 214. Circles indicate relative abundances. p values are presented for correlations with $p \leq 0.05$. Figure 4.2. Statistical measurements (maximum, minimum, mean, and standard deviation) of % MLS at the studied Sites 807 and 214.
(Figure 5b), which suggests coeval thickening of the mixed layer in the western Pacific (perhaps accompanied by thermocline tilt, Figure 6) and in the eastern Indian Ocean. The mixed-layer taxa, in general, are oligotrophic, flourishing in a well-mixed water column and are less abundant in upwelling systems (Brock et al., 1992). However, *G. glutinata* is an opportunistic species that prefers to dwell in nutrient-rich mixed-layer waters (Crundwell et al., 2008; Mohtadi et al., 2005). According to our data set from Site 807, *G. glutinata* shows an opposite trend as compared to the MLS with a stepwise decrease from ~3.15 to 1.6 Ma, indicating oligotrophic conditions at this location (Figure 4). At ODP Site 806, which is near Site 807, LaRiviere et al. (2012), based on $\Delta^{18}O_{subsurface}$ values between subsurface dwellers and surface dweller foraminifera at ODP Site 806 (orange) (LaRiviere et al., 2012), (b) % MLS at Site 807 (orange) and Site 214 (blue) (present study). (c) Concentration of alkenones C$_{37}$ Total (nmol/g) at ODP Site 846 (Lawrence et al., 2006). (d) SST based on $U^\text{37}_\text{C}$ at ODP Site 138-846 $U^\text{37}_\text{C}$ (Herbert et al., 2016) (orange) and SST based on TEX$_{86}$ at ODP Site 850 (Zhang et al., 2014) (blue). (e) SST based on $U^\text{37}_\text{C}$ at ODP Site 1125 (Fedorov et al., 2015). (f) SST based on $U^\text{37}_\text{C}$ at ODP Site 1143 (orange) (Li et al., 2011) and at ODP Site 1147/1148 (blue) (Jia et al., 2008). IG = Indonesian Gateway; WPWP = West Pacific Warm Pool; MPWP = Mid-Pliocene Warm Period.

**Figure 5.** Proxy records from ODP Site 807 and DSDP Site 214 compared with those from the other sites. (a) Percentage distribution of *Globigerinita glutinata* (blue, present study) and the $\delta^{18}O$ differences ($\Delta\delta^{18}O$ values) between subsurface dwellers and surface dweller foraminifera at ODP Site 806 (orange) (LaRiviere et al., 2012).
The intensification of the Walker and Hadley circulation cells has also been linked to the EEP thermocline shoaling (Brierley et al., 2009; Ford et al., 2015).

Our *Globigerina glutinata* population data suggest shoaling of the WEP thermocline, transferring heat across the Indo-Pacific and suggest an intensification in the Walker Circulation around 3 Ma. *Globigerinoides tumida* populations in the WEP fluctuated from 5 to ~3.4 Ma, yet MLS populations remain stable with lower values between 5 and 4 Ma and increased slightly from 4 to 3.15 Ma. At the same time, the $\Delta^{18}O_{\text{sub}}$ values at Site 806 indicate a gradual thermocline shoaling in the western Pacific (Figure 5a). Fluctuations in the *G. glutinata* populations appear to be independent of thermocline shoaling in the WEP as the thermocline is deeper and the nutrients are beyond the vertical reach of Ekman pumping (the component of Ekman transport that results in downwelling due to the convergence of water and because the WPWP is so thick, the Ekman component fails to bring cold water to the sea surface) (Richards & Pollard, 1991).

However, between ~3.4 and 3.1 Ma *G. glutinata* shows a slight increase in its population (up to ~5.46%) with a reduced $\Delta^{18}O_{\text{sub}}$ surface gradient (Figure 5a), which could be related to the shoaling of the WPWP with lowered sea level in the region (up to ~60 m) between 3.45 and 3.25 Ma as reported by Miller et al. (2012). Afterward, a major transgression occurs around 3.25 Ma followed by a decrease in
G. glutinata population (from 5.46% to 0.00%) in the WEP and a sharp increase in MLS numbers (at both Sites 807 and 214) starting at ~3.15 Ma (Figure 4), which suggests a gradual development of a thick mixed layer resulting from the constriction of the IG and hints at the development of the oligotrophic WPWP during the late Pliocene.

We propose that the WPWP continued to evolve toward its modern state despite basin-wide thermocline shoaling and that the establishment of oligotrophic conditions within the WPWP began at ~3.15 Ma. The MLS census counts at both Sites 807 and 214 show a significant increase from ~3.15 to 1.91 Ma (see Table S3 for details). This increase at Site 807 coincides with the intensification of tropical Pacific thermocline tilt and shoaling in the EEP as proposed by Ford et al. (2015) (Figures 6a and 6b). The thermocline shoaling in the WEP however was not sufficient to significantly influence SSTs (as in the EEP) (Ford et al., 2015; LaRiviere et al., 2012).

5.2. Spatial Extent of the WPWP Through Time

Paleoclimate data indicate that the meridional and zonal SST gradients were weaker in the early Pliocene warm period (5–3 Ma) (Brierley et al., 2009; Burls & Fedorov, 2014; Fedorov et al., 2006, 2013; Wara et al., 2005). Studies have also shown that the zonal SST gradient in the equatorial Pacific and the meridional SST gradient between the tropics and midlatitudes are tightly linked (Burls & Fedorov, 2014; Brierley et al., 2009; Martinez-Garcia et al., 2010). The WPWP was spatially expanded during the early Pliocene, and the warm pool then gradually contracted, zonally as well as meridionally toward the equator (Brierley et al., 2009). To study how the zonal and meridional contraction resulted in the evolution of the WPWP, we compared our G. glutinata abundances and MLS data with previous records from the EEP, WEP, SCS, and Chatham Rise off New Zealand.

5.2.1. Zonal Contraction

To study the zonal contraction of the warm pool, we compared surface (using T. sacculifer Mg/Ca) and subsurface (using G. tumida Mg/Ca) temperature records from the WEP (ODP Site 806) and EEP (ODP Site 849 and Site 847) (Ford et al., 2015, 2012; Wara et al., 2005) to our G. glutinata and MLS abundance data (Figures 5 and 6). During the early Pliocene, zonal SST was reduced as a result of the basin-wide deeper thermocline in the EEP and WEP (Ford et al., 2015). Furthermore, the Cold Tongue (CT) was not as extensive as it is today in the EEP during the early Pliocene (Ford et al., 2015, 2012; Fedorov et al., 2006; Wara et al., 2005). Both surface and subsurface temperature records from the EEP and WEP point to equatorial Pacific thermocline shoaling and cooling and suggest that the zonal SST contrast began to intensify from ~4 Ma (Figures 6b and 6c) as a result of the CAS closure (Ford et al., 2015, 2012; Steph et al., 2010; Wara et al., 2005). At ~4.0 Ma, the gradual shoaling of the tropical thermocline influenced SSTs and ocean-atmosphere coupling in the CT region. Subsequently, wind-induced upwelling in the EEP intensified at ~3 Ma (Fedorov et al., 2006; Ford et al., 2015; Lawrence et al., 2006). The effect of this basin-wide shoaling (and/or cooling) was not sufficient to greatly impact SSTs in that region, resulting in the equatorial Pacific thermocline tilt and strong zonal SST contrast (Fedorov et al., 2006, 2015; Ford et al., 2015; Wara et al., 2005). Liu and Huang (1997) suggested that the Pacific Walker Circulation is coupled to the zonal SST gradient and that the intensity of these circulations determines the strength of the oceanic volume transport.

On the other side of the Pacific, the constriction of the IG, as a result of northward drift of New Guinea, played a major role in blocking the warm equatorial surface water in the WEP region (Cane & Molnar, 2001; Karas et al., 2009). Furthermore, northward drift of New Guinea would change the source of the EUC in the Pacific toward a stronger Southern Ocean component. The EUC upwells in the EEP with nutrient-rich waters emanating from the Southern Ocean (Lawrence et al., 2006; Sarmiento et al., 2004; Toggweiler et al., 1991). Lawrence et al. (2006) have posited an increase in primary productivity in the eastern Pacific based on alkenone concentrations (C_{37} Total) at Site 846 (Figure 5c). This increase in EEP primary productivity is near synchronous with the development of WPWP (Figures 5b and 5c). Primary productivity in the EEP is closely linked to the intermediate nutrient-rich cold waters from the high latitudes of the North and South Pacific, where the South Pacific contributes more nutrients to the waters that are upwelled in the EEP (Sarmiento et al., 2004; Toggweiler et al., 1991)—a process posited to be regulated by the ensuing supply of iron (Drenkard & Karnauskas, 2014; Karnauskas & Cohen, 2012). The intermediate nutrient-rich cold waters from the Southern Ocean high latitudes are transported to the EEP, through the
EUC, and are thought to be responsible for increased productivity in the region as well as the shoaling of the east Pacific thermocline (Bryden & Brady, 1985; Sarmiento et al., 2004; Toggweiler et al., 1991). Our MLS population abundances at both Sites 807 and 214 are near synchronous with primary production in the EEP around ~3 Ma (Figures 5b and 5c).

These results indicate that the reorganization and constriction of the IG is linked to changes in the EUC, intensification of the Pacific Walker Circulation, and upwelling in the CT region (Fedorov et al., 2006; Ford et al., 2015; Lawrence et al., 2006; Steph et al., 2010; Tierney et al., 2019; Toggweiler et al., 1991). Although changes in the Walker Circulation are coupled to the evolution of ENSO events, there is ongoing debate on the modulation of interannual SST variability by alterations in the mean state of the Pacific Ocean (Tierney et al., 2019; White & Ravelo, 2020) and its detection (Tindall et al., 2017). Nevertheless, SST data from Zhang et al. (2014) at Site 850 and Herbert et al. (2016) at Site 846 from EEP also show a gradual decrease in the SST at the same time, which further suggests thermocline shoaling and emergence of the CT in the EEP at ~3.15 Ma (Figure 5e). Thus, it appears that the WPWP was not well established relative to present-day conditions prior to ~3.15 Ma and thus could be related to a weaker Walker Circulation (Tierney et al., 2019).

We propose a feedback between the gradual development of the warmer waters of the WPWP and the intensification of the Pacific Walker Circulation. We suggest that the Walker Circulation itself intensified as a result of increasing Pacific zonal SST contrast, which in turn strengthened due to the constriction of the IG since ~4 Ma (Figure 6). This further warmed the WPWP. Moreover, we propose that oligotrophic conditions were enhanced in the WEP due to the increased advection of surface waters from the EEP resulting from the intensified Walker Circulation at ~3.15 Ma. We suggest that these dynamics are reflected in our data sets as an increase in MLS abundance and the coeval decrease of G. glutinata populations (Figures 5a and 5b). The trends in MLS abundance at Site 807 mirrors that of Site 214 between ~3.15 and 1.6 Ma and alongside the observation of maximum abundances at ~2 Ma strongly point to links with the intensification of the Walker Circulation (Martínez-García et al., 2010; Ravelo et al., 2004) (Figure 6). This suggests that surface ocean changes at both sites were near synchronous and underpins a linkage between the formation of the WPWP and the constriction of the IG.

5.2.2. Meridional Contraction

As the Walker Circulation cell strengthened along the equator, strong CT upwelling emerged in the EEP and the zonal extent of the warm pool reduced (Fedorov et al., 2015; Wara et al., 2005). Likewise, the reduction of the meridional extent of the WPWP has also been associated with a weak HC and vice versa (Brierley et al., 2009; Jia et al., 2008).

The meridional extent of the WPWP contracted over the Plio-Pleistocene as shown by the U37K-based SST records from the South China Sea and near New Zealand (Figures 5e and 5f). To explore the meridional spatiotemporal changes and related development of the WPWP, we compared our MLS and G. glutinata census records with previous work from the SCS and a site offshore of eastern New Zealand. The SST records from the SCS show a reduction in SSTs at ~3 Ma at ODP Sites 1147 and 1148 (Jia et al., 2008), located at the edge of the warm pool, whereas at ODP Site 1143 SSTs remained relatively stable (Li et al., 2011). Prior to ~3 Ma, SSTs were similar at both sites (Figure 5f). Further, U37K-SST data from the SCS suggest contraction of the WPWP toward the equator, that is, toward Site 807 in the late Pliocene (Figure 5f). U37K-SST data from ODP Site 1125 (Fedorov et al., 2015) also show a fall in SST at ~3.15 Ma, suggesting a contraction of a formerly expanded warm pool toward the equator from the Southern Ocean during this time (Figure 5e). Fedorov et al. (2015) suggest that the zonal SST gradient across the equatorial Pacific is tightly linked to the meridional SST gradient via the wind-driven circulation and upper-ocean stratification. Comparison of our MLS data from Sites 807 and 214 with the SST records from SCS and near New Zealand indicate a progressive evolution of the WPWP with increasing meridional SST in the tropical western Pacific.

6. Conclusions

The evolutionary record of the WPWP was reconstructed using foraminiferal abundances at Sites 807 and 214 in the WEP Ocean and eastern Indian Ocean, respectively. We find a stark decrease in productivity and increase in mixed-layer thickness beginning around 3.15 Ma at the study sites, suggesting that such surface oceanographic changes were linked to the development of the Indo-Pacific warm pool. Our findings
support previously published work and provide further evidence for the evolution of the Indo-Pacific warm pool during the late Pliocene. We conclude that the evolution of the Indo-Pacific warm pool was closely linked to the progressive narrowing of the IG and intensification of the Walker Circulation. We posit that this tectono-oceanic event greatly affected global and regional climate evolution with far-reaching impacts (e.g., poleward heat transport, ENSO, east African aridification, and Indian Monsoon).

**Data Availability Statement**

The data have been uploaded on Pangaea.de. (https://doi.pangaea.de/10.1594/PANGAEA.922183).

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