TECHNICAL RESPONSE

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Response to Comment on "A 12-million-year temperature history of the tropical Pacific Ocean"

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Contrary to our conclusions, Ravelo *et al*. argue that our TEX_{86}-based sea surface temperature (SST) records do not conflict with the supposition of "permanent El Niño–like" conditions during the early Pliocene. We show that the way Ravelo *et al*. treat the existing temperature data perpetuates an inaccurate impression of cooler Pacific warm-pool SSTs and low equatorial temperature gradients in the past.

At the center of the discussion raised by Ravelo *et al.*'s Comment (*1*) is how ancient data should be compared with modern conditions and how existing SST records should be compiled and/or screened. Our conclusion that the western Pacific warm-pool temperatures cooled for the past 12 million years is based on biomarker sea surface temperature (SST) reconstructions ($U_{37}^{K'}$ and TEX_{86}), which show long-term patterns of cooling into the Quaternary in both the upper and lower ranges of temperature variability (*2*). The SST calibration uncertainty of TEX_{86} is larger than that for $U_{37}^{K'}$, but, where available, both proxies show similar cooling (*2*, *3*). During the Pliocene, our TEX_{86} data show an elevated upper and lower temperature range compared with both the Holocene and average Quaternary. The warmest TEX_{86}-based SST at site 806 during the Pliocene is 30.0°C (using Kim10 calibration), 1.9°C higher than the core-top estimate of 28.1°C according to Ravelo *et al.* (*1*). Further, if we account for a cool bias in TEX_{86} temperatures and apply the recent Bayesian TEX_{86} calibration (*4*), temperatures in the warm pool are revised to 32.8°C—4.7°C. In contrast, Ravelo *et al.* argue that our Pliocene TEX_{86} temperatures in the Pacific warm pool are similar to modern conditions by comparing multimillion-year "average" Pliocene TEX_{86} temperatures between 3.5 and 5.0 Ma with modern temperature observations and core-top signatures at site 806. We suggest that this type of evaluation generates comparatively cooler ancient temperatures, because the "Pliocene average" is a mean of SST over many climate cycles, whereas the "core top" is a snapshot of the warm Holocene. For example, if we apply Ravelo *et al.*'s approach to assess Pliocene deep-sea temperatures using the global benthic $\delta^{18}O$ stack (*5*), the "Pliocene benthic $\delta^{18}O$ average" between 3.5 and 5.0 Ma is 3.01 per mil (‰)—0.22‰ more negative than the core-top value of 3.23‰ (Fig. 1). Even if we ignore ice-volume effects from the Pliocene to the Holocene, a 0.22‰ difference translates to negligible temperature difference (<1°C) between the deep water of the Pliocene and today. If only warm interglacials (marine isotope stage 5, 123,000 years ago, $\delta^{18}O$ = 3.10‰ and marine isotope stage 11, 405,000 years ago, $\delta^{18}O$ = 3.11‰) are compared against the "Pliocene benthic $\delta^{18}O$ average," there is even a smaller $\delta^{18}O$ difference (≤0.1‰), suggesting that the Pliocene was only as warm as the interglacials of the Pleistocene (*6*, *7*). Similarly, Ravelo *et al.*'s treatment of SST data creates a cool-bias impression that Pliocene warm-pool temperatures were the same as today.

In contrast to secular cooling indicated by TEX_{86} and $U_{37}^{K'}$, Mg/Ca-based SSTs from two western equatorial Pacific sites appear relatively invariant or perhaps warm toward the present (Fig. 2). Biomarker and Mg/Ca trends are not equivalent but are treated as such in Ravelo *et al.*'s Comment. The "permanent El Nino" supposition was founded on Mg/Ca-based warm-pool temperatures, but there are several reasons why Mg/Ca SSTs are likely not accurate. Evidence supports changing seawater Mg/Ca ratios with time that must affect SST reconstructions over multimillion-year time scales (*8*). Foraminiferal Mg incorporation also appears susceptible to seawater salinity (*9*), pH (*10*), and carbonate ion concentration (*11*). Last, the impact of early diagenesis on carbonate Mg concentration cannot be ruled out, given that the pore-water Sr^{2+} concentration profile at site 806 has [Sr^{2+}] that are 10 times as high as modern seawater levels (*12*). These factors, in combination with our results (*2*) and others (*3*), erode confidence in Pliocene-age Mg/Ca-SST reconstructions of Pacific warm-pool temperatures. If warm-pool Mg/Ca temperatures and trends are compromised, so is the notion of invariant warm-pool temperatures. Also, we take the position that Mg/Ca and biomarker SSTs cannot be collectively applied (as performed in Ravelo *et al.*'s Comment) to make statements about Pliocene trends or temperatures just because these SST records happen to intersect during this time (Fig. 2). Further, if warm-pool Mg/Ca SSTs are compromised, then TEX_{86} data currently remain as the best available temperature records because $U_{37}^{K'}$ data reach maximum values by the Pliocene and cannot reveal whether warm pool temperatures exceeded ~28.5°C.

Ravelo *et al.* further state that zonal gradients resulting from our data do not conflict with the

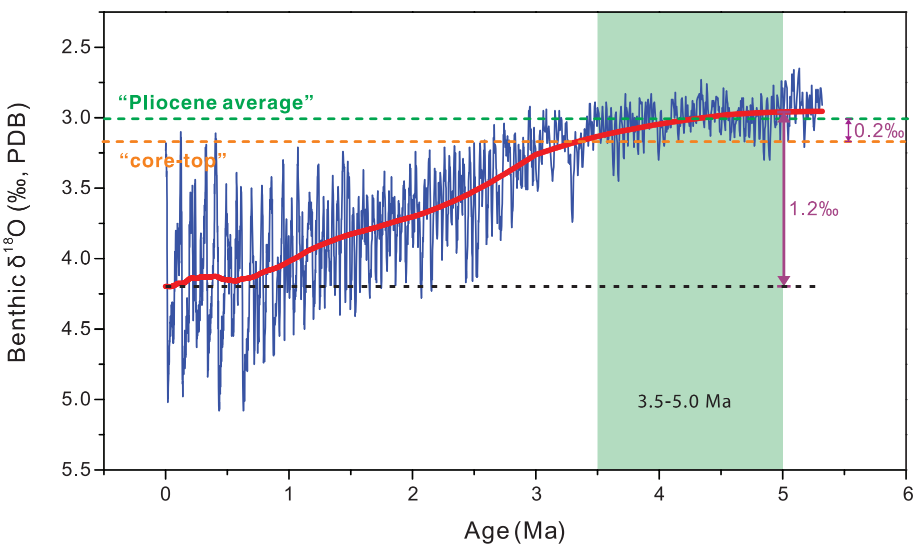

Fig. 1. Comparisons between the "Pliocene average (averaging between 3.5 and 5.0 Ma)" and the "core-top" benthic $\delta^{18}O$ values in the LR04 global stack (*5*). The difference between the "Pliocene average" and "core-top" is only 0.22‰. In contrast, the difference between $\delta^{18}O$ at 5 Ma and 0 Ma in the long-term trend (500-point running average, red curve) of the LR04 record is ~1.2‰.

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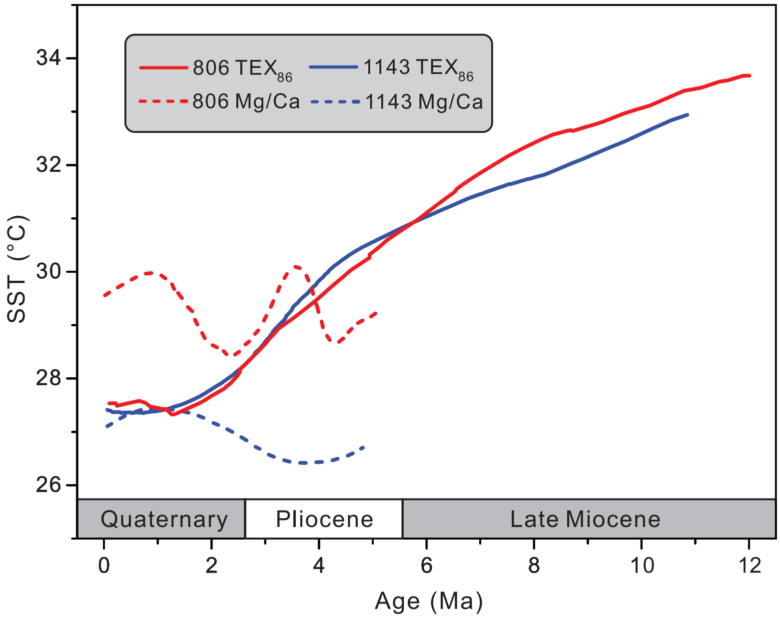

Fig. 2. Trends of TEX_{86}- and Mg/Ca-SSTs from sites 806 (*2*, *14*) and 1143 (*2*, *3*) in the Pacific warm pool. TEX_{86} data are converted to SSTs using the recently introduced Bayesian calibration (*4*). Refer to our original publication (*2*) for the results using Kim10 calibration (*15*). Trends are calculated by applying 50-point fast Faurier filters.

supposition of permanent El Niño–like conditions, which was characterized by many of the same authors as recently as 2013 as "a climate with almost no zonal sea surface temperature (SST) gradients (~1°C or less)" (*13*). In their Comment, Ravelo *et al.* argue that TEX_{86} SSTs in the cold tongue are cold biased, whereas TEX_{86} in the warm pool is accurate. Consequently, they ignore TEX_{86} data in the cold tongue and restrict their analysis to one TEX_{86} record from site 806 and one $U^{K'}_{37}$ record from the cold-tongue region (Site 850) and derive a small zonal temperature gradient through the Pliocene. Given that the modern Pacific warm pool is larger than the continental United States and that the cold tongue extends a few thousand kilometers, we take the position that the application of multiple sites yields a better perspective of regional paleotemperatures (*2*). We also recognize that core-top TEX_{86}-SSTs from both open eastern and western equatorial Pacific regions (using Kim10 calibration) appear cooler than SSTs. The down-core TEX_{86}-SSTs are also cooler than $U^{K'}_{37}$-SST records when $U^{K'}_{37}$ indices are not at their maximum value (e.g., sites 806 and 850) (*2*). Consequently, TEX_{86} appears to be underestimating SST in both the east and the west, not just in the eastern equatorial Pacific. Because a cool bias persists in both the east and the west, evaluation of zonal temperature gradients is still valid between TEX_{86} records, as we considered in our paper (*2*). However, our interpretations also consider all the available $U^{K'}_{37}$ records that are below their maximum values. That analysis showed that 75% of the modern or 79% of the mean Quaternary zonal temperature gradient was preserved during the Pliocene, whereas 70% of the mean Quaternary zonal temperature gradient was represented during the Late Miocene. Although this indicates that the zonal gradient was slightly reduced, it is far from the characteristics of a "permanent El Niño–like" state that most associate with the supposition.

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