Pliocene warmth and gradients

To the Editor — The Pliocene epoch (5.3–2.6 Ma) generates continued debate as an example of a warm climate with external forcing similar to the present day[1]. O'Brien *et al.*[2] presented new multi-proxy sea surface temperature (SST) reconstructions from the South China Sea, adding to this debate. Based on their records, and a hypothesized seawater chemistry adjustment to temperature reconstructions previously derived from the Mg/Ca ratios of planktonic foraminifera, they suggest that the western Pacific warm pool was "2 °C warmer than today" in the Pliocene. This contradicts previous evidence of long-term stability in warm pool SSTs[1,3], but possibly reconciles temperature reconstructions and climate model simulations. Here we raise several points contrary to those conclusions.

All of the available mid-Pliocene SST data from the heart of the warm pool agree within the data uncertainty (Fig. 1) and suggest no significant warming. For their site in the western Pacific (ODP 806), the unadjusted Mg/Ca temperature estimate[3] for the mid-Pliocene[4] (Fig. 1) is close to estimates from faunal assemblage data[4] and TEX$_{86}$ approaches[5], whereas alkenone-based $U^{k'}_{37}$ values are too close to saturation to provide a reliable estimate of sea surface temperature. In the heart of the east Pacific cold tongue (ODP 847), both Mg/Ca and alkenone palaeothermometry agree[6]. The global seawater chemistry correction applied by O'Brien *et al.*[2] breaks this close correspondence at these respective locations. Consequently, the large discrepancy between the Mg/Ca estimate and other SST estimates from the South China Sea (ODP 1143) may instead be a local feature. We argue that this marginal sea is not an appropriate location to characterize the open ocean warm pool: a temperature increase of 2 to 3 °C in the South China Sea could result from the warm pool's meridional expansion during the Pliocene[1], rather than a uniform warming across the western Pacific.

When dealing with signals as small as expected in the warm pool, defining our temporal reference frame also requires careful attention. This region has seen over 0.5 °C of warming since 1950 (defined as 0 years before present), and more since pre-industrial times. The Pliocene Model Intercomparison Project (PlioMIP, ref. 7) simulates conditions of a mid-Pliocene interglacial and the differences from the pre-industrial. An alternate approach for the interpretation of coarse-resolution data uses a calculation of the difference from the youngest point of a long-term (approximately 400 kyr) mean[1–3,6]. When comparing averages from coarse-resolution datasets to simulations referenced to pre-industrial conditions, this alternative approach results in an approximately +1 °C offset from traditionally calculated differences (Fig. 1). Also, the PlioMIP simulations are driven by CO$_2$ levels at

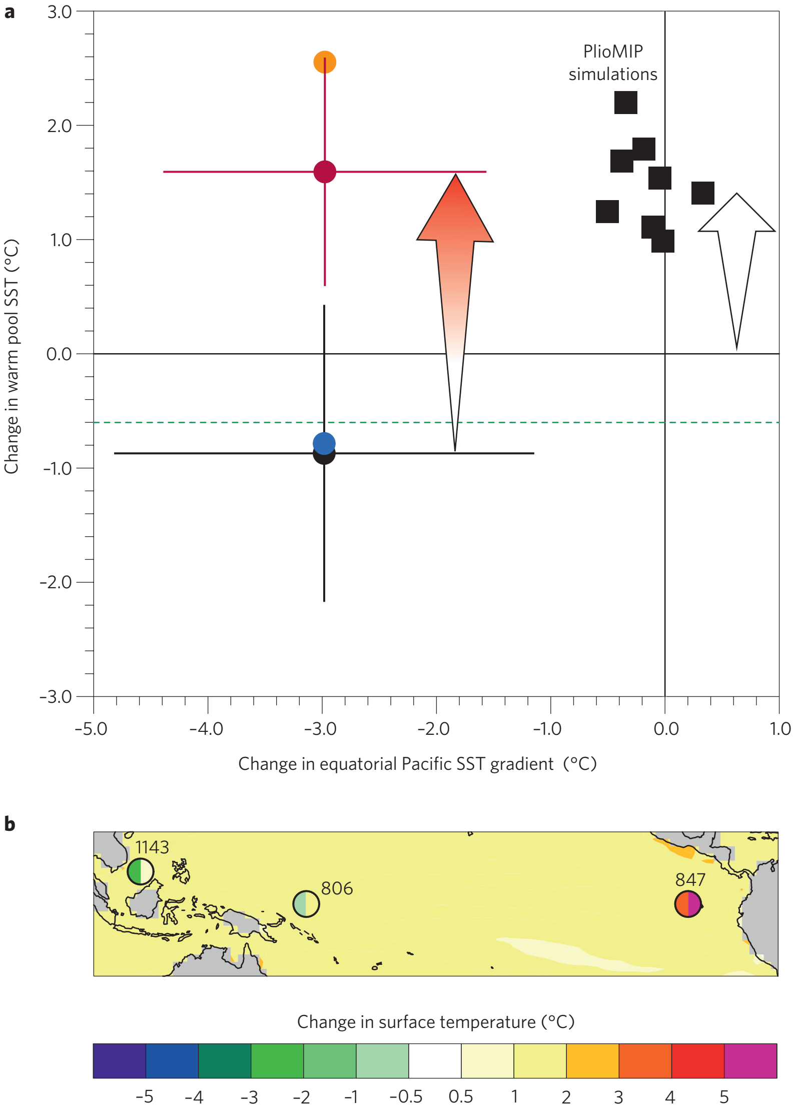

Figure 1 | Reconstructed and simulated mid-Pliocene SST changes from pre-industrial conditions. **a**, The Mg/Ca-based reconstructions from Wara *et al.*[3] are shown in black (with their stated errors); and after the proposed chemistry adjustment of O'Brien *et al.*[2] (red, with stated errors from ref. 2). The orange circle shows the adjusted values compared with the long-term mean[2] rather than the pre-industrial. Equivalent faunal reconstructions[4] (blue) and the TEX$_{86}$ reconstruction[5] at ODP 806 (green line) are also shown. For the PlioMIP simulations[7] the change in the warm pool temperature is relative to the maximum simulated value on the Equator. Red and black arrows show the direction of both an Mg/Ca seawater adjustment[2] and the modelled response of increasing carbon dioxide[7], respectively. **b**, The ODP sites used by O'Brien *et al.*[2] are shown without (left) and with (right) their proposed seawater Mg/Ca correction. The PlioMIP mean temperature changes are shown in the background.

the upper end of Pliocene estimates[8], so one might anticipate them to simulate higher temperatures than those found in the reconstructions of the mean mid-Pliocene temperatures.

We feel that from a dynamical perspective, the most interesting feature of Pliocene warm climates is the weak zonal (Fig. 1) and meridional temperature gradients in the tropics[9]. These weakened gradients are not captured by the PlioMIP simulations. However, the inability of climate models to simulate the extent and patterns of Pliocene warmth[7], specifically within the sub-tropics and equatorial upwelling regions, is a problem unresolved by a global seawater chemistry correction (Fig. 1), or by a higher Earth-system sensitivity[8] to CO_2 forcing, as suggested in an accompanying News and Views[10]. Solving the problem will require the identification of mechanisms that can support weak temperature gradients[1,9], possibly through better constraints on climate feedbacks in climate models[1].

References
1. Fedorov, A. V. *et al. Nature* **496,** 43–49 (2013).
2. O'Brien, C. L. *et al. Nature Geosci.* **7,** 606–611 (2014).
3. Wara, M. W., Ravelo, A. C. & Delaney, M. L. *Science* **309,** 758–761 (2005).
4. Dowsett, H. J., Robinson, M. M., Stoll, D. K. & Foley, K. M. *Stratigraphy* **7,** 189–198 (2010).
5. Zhang, Y. G., Pagani, M. & Liu, Z. *Science* **344,** 84–87 (2014).
6. Dekens, P. S., Ravelo, A. C., McCarthy, M. D. & Edwards, C. A. *Geochem. Geophys. Geosyst.* **9,** Q10001 (2008).
7. Haywood, A. M. *et al. Clim. Past* **9,** 191–209 (2013).
8. Pagani, M., Liu, Z., LaRiviere, J. & Ravelo, A. C. *Nature Geosci.* **3,** 27–30 (2009).
9. Brierley, C. *et al. Science* **323,** 1714–1718 (2009).
10. Pagani, M. *Nature Geosci.* **7,** 555–556 (2014).

Chris Brierley[1]*, Natalie Burls[2], Christina Ravelo[3] and Alexey Fedorov[4]
[1]Department of Geography, University College London, London WC1E 6BT, UK. [2]Department of Atmospheric, Oceanic & Earth Sciences, George Mason University, Fairfax, Virginia 22030, USA. [3]Department of Ocean Sciences, University of California, Santa Cruz, California 95064, USA. [4]Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06511, USA.
*e-mail: c.brierley@ucl.ac.uk

Reply to 'Pliocene warmth and gradients'

O'Brien *et al.* reply — Brierley *et al.*[1] question our findings of elevated temperatures in the tropical warm pools during the Pliocene[2]. Focusing specifically on the mid-Pliocene warm period (about 3.3 to 3 million years ago), as framed by Brierley *et al.*, we continue to find evidence for warmer than Holocene temperatures in the western Pacific warm pool in good agreement with PlioMIP simulations, especially in light of new $p_{\mathrm{CO_2}}$ reconstructions[3].

First, seawater Mg/Ca values were almost certainly lower than modern during the Pliocene (for example, ref. 4), although the exact magnitude and implications for the Mg/Ca ratio of foraminiferal calcite remain uncertain[5]. Nevertheless, if the western Pacific warm pool was the same temperature as pre-industrial times, as Brierley *et al.* contest, we would expect the Mg/Ca values of the foraminifera to be lower than those of the Holocene. Therefore, the observation of similar Holocene and mid-Pliocene Mg/Ca values indicates that sea surface temperatures were warmer than during the pre-industrial Holocene in the western Pacific warm pool, regardless of the correction used.

Second, Brierley *et al.* suggest that because sea surface temperature (SST) estimates based on uncorrected Mg/Ca and the alkenone $U^{k'}_{37}$ proxy agree at site ODP 847 in the east tropical Pacific, the Mg/Ca seawater correction may be site-specific, and therefore unnecessary at site ODP 806 in the heart of the warm pool. However, they provide no mechanistic rationale for this. Moreover, as we discussed in the Supplementary Information of our Article, five out of six low-latitude sites for which Mg/Ca and $U^{k'}_{37}$ palaeotemperature estimates exist show better agreement when the seawater Mg/Ca correction is applied. We also argue that faunal-based temperatures that appear to confirm little warming are biased by the upper limit of the modern calibration dataset, which is about 30 °C (ref. 6).

Third, we can also rule out a simple expansion of the western Pacific warm pool based on TEX^{H}_{86} and Mg/Ca temperature reconstructions from the South China Sea (ODP 1143) and Mg/Ca temperature estimates from the warm pool centre (ODP 806). Specifically, the Holocene Mg/Ca temperature difference between the sites[7] persists throughout our 5-million-year records[2,8], implying that both the western Pacific and South China Sea were 1 to 2 °C warmer than Holocene during the Mid-Pliocene.

Fourth, a comparison between Plio–Pleistocene TEX^{H}_{86}; $U^{k'}_{37}$ and Mg/Ca temperature estimates (with an Mg/Ca correction applied) and corresponding Holocene core-tops also indicates that the western Pacific warm pool, South China Sea and western Atlantic warm pool were warmer than Holocene estimates (Supplementary Fig. 1). Similarly, applying a regional, Bayesian-based TEX_{86} calibration[9] yields Pliocene SSTs that are ~1–2 °C higher than modern, measured SSTs for both ODP 806 and ODP 1143. We also point out that for all of these proxy approaches, the Pliocene data points represent an average of several thousand years, and thus do not necessarily represent maximum Pliocene warmth.

Finally, the long-term trends in the TEX^{H}_{86} data from the heart of the western Pacific warm pool[10] and southern South China Sea[2,10] clearly demonstrate that the warm pool temperatures have cooled from the Late Miocene to the Pleistocene (Supplementary Fig. 1a,b). In summary, the data we presented in ref. 2 and provide here strongly suggest that the warm pools of the Atlantic and Pacific were warmer than the Holocene during the Mid-Pliocene warm period and Pliocene as a whole.

References
1. Brierley, C. *et al. Nature Geosci.* **8,** 419–420 (2015).
2. O'Brien, C. L. *et al. Nature Geosci.* **7,** 606–611 (2014).
3. Martínez-Botí, M. A. *et al. Nature* **518,** 49–54 (2015).
4. Lowenstein, T. K., Timofeeff, M. N., Brennan, S. T., Hardie, L. A. & Demicco, R. V. *Science* **294,** 1086–1088 (2001).
5. Evans, D. & Müller, W. *Paleoceanography* **27,** PA4205 (2012).
6. Reynolds, R. W. & Smith, T. M. *J. Climate* **8,** 1571–1583 (1995).
7. Locarnini, R. A. *et al.* in *NOAA Atlas NESDIS 68* Vol. 1 (ed. Levitus, S.) (US Government Printing Office, 2010).
8. Wara, M. W., Ravelo, A. C. & Delaney, M. L. *Science* **309,** 758–761 (2005).
9. Tierney, J. E. & Tingley, M. P. *Geochim. Cosmochim. Acta* **127,** 83–106 (2014).
10. Zhang, Y. G., Pagani, M. & Liu, Z. *Science* **344,** 84–87 (2014).

Charlotte L. O'Brien[1,2,3]*, Gavin L. Foster[4], James W. B. Rae[5] and Richard D. Pancost[1,2]
[1]Organic Geochemistry Unit, School of Chemistry, University of Bristol, Bristol BS8 1TS, UK. [2]Cabot Institute, University of Bristol, Bristol BS8 1UJ, UK. [3]Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK. [4]Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton SO14 3ZH, UK. [5]Department of Earth and Environmental Sciences, Irvine Building, University of St Andrews, St Andrews KY16 9AL, UK.
*e-mail: charlotte.obrien@earth.ox.ac.uk