LETTER

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Permanent El Niño during the Pliocene warm period not supported by coral evidence

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The El Niño/Southern Oscillation (ENSO) system during the Pliocene warm period (PWP; 3–5 million years ago) may have existed in a permanent El Niño state with a sharply reduced zonal sea surface temperature (SST) gradient in the equatorial Pacific Ocean[1]. This suggests that during the PWP, when global mean temperatures and atmospheric carbon dioxide concentrations were similar to those projected for near-term climate change[2], ENSO variability—and related global climate teleconnections—could have been radically different from that today. Yet, owing to a lack of observational evidence on seasonal and interannual SST variability from crucial low-latitude sites, this fundamental climate characteristic of the PWP remains controversial[1,3–10]. Here we show that permanent El Niño conditions did not exist during the PWP. Our spectral analysis of the δ^{18}O SST and salinity proxy, extracted from two 35-year, monthly resolved PWP *Porites* corals in the Philippines, reveals variability that is similar to present ENSO variation. Although our fossil corals cannot be directly compared with modern ENSO records, two lines of evidence suggest that Philippine corals are appropriate ENSO proxies. First, δ^{18}O anomalies from a nearby live *Porites* coral are correlated with modern records of ENSO variability. Second, negative-δ^{18}O events in the fossil corals closely resemble the decreases in δ^{18}O seen in the live coral during El Niño events. Prior research advocating a permanent El Niño state may have been limited by the coarse resolution of many SST proxies, whereas our coral-based analysis identifies climate variability at the temporal scale required to resolve ENSO structure firmly.

There is still considerable debate over the characteristics of ENSO during the PWP, even though several previous models and geochemical proxy-based reconstructions have been generated[1,3–10]. The clearest controversy has appeared in recent publications in which two teams using the same geochemical approaches with the same sediment cores from western and eastern Pacific sites obtained opposing results for the climatic conditions related to ENSO during the PWP in the Pacific Ocean. Both studies combined Mg/Ca and δ^{18}O ratios for the same species of planktonic foraminifera to reconstruct the western and eastern gradients of SST and salinity. These factors constrain the background climate state and the variability of ENSO occurrence. The first-presented work[5] on a strong SST gradient between the western and eastern equatorial Pacific concluded that a La Niña-like state was dominant throughout the PWP. Shortly thereafter, it was suggested[1], on the basis of Mg/Ca and δ^{18}O data with higher temporal resolution from the same set of sediment cores, that there were permanent El Niño-like conditions during the PWP. In a warm and wet climatic background with global warming and freshening, the larger and fresher water mass that permanently exists in the eastern Pacific Ocean might prevent periodic occurrences of El Niño, or the newer and stronger heat conditions might lead to similar, stronger and more frequent El Niño events. Reconstructing ENSO characteristics in the PWP is important for understanding future climate change scenarios. Both permanent El Niño- and La Niña-like conditions have been found in alkenone-based SST reconstructions[9,10] and model-based estimations[6,7]. Owing to the limited temporal resolution of ocean sediment cores, however, no direct evidence exists about the variation of ENSO phenomena, which have seasonal and interannual variabilities caused by interactions between the ocean and atmosphere.

Today ENSO is defined as a shifting of the western Pacific warm pool (WPWP), the warmest surface sea water in the western Pacific, towards the eastern Pacific in 3–7-yr intervals[11]. This warm water mass becomes thicker in the eastern Pacific and prevents upwellings in this region during El Niño conditions. Simultaneously, in the atmosphere the Hadley cell and Walker circulation shift towards the eastern Pacific side, resulting in cooler and drier conditions on the western side of the Pacific Ocean.

Coral skeletons in tropical and subtropical regions hold a wealth of information about past climate changes with monthly temporal resolution from the geochemical signatures of their annual bands[12–14]. The δ^{18}O ratio in coral skeletons has been widely used to reconstruct past SSTs and water balance[12–15]. The utility of skeletal δ^{18}O from the coral genus *Porites* in monitoring interannual climate fluctuations in the tropical Pacific region has been widely demonstrated for both modern[11] and fossil corals[13,14]. The effect of ENSO on *Porites* δ^{18}O records in the WPWP region has also been evident in previous studies on living and fossil specimens[14,15]. During El Niño events, the combined effect of lower SST and reduced monsoon rainfall (higher δ^{18}O values of sea water ($\delta^{18}O_w$)) has served to increase δ^{18}O in *Porites*, in association with prevailing higher monsoon rainfall (lower $\delta^{18}O_w$ values). El Niño events are triggered when eastern equatorial Pacific SSTs are unusually high, and these events are typically associated with cooler SSTs[16] and below-average monsoon rainfall[17] in the southwestern North Pacific. In contrast, changes in SSTs in the southwestern North Pacific are less marked during La Niña events (when the eastern equatorial Pacific is cooler than average), but rainfall is enhanced owing to more vigorous summer monsoons. At the PWP fossil coral sampling site in the Philippines, the interannual climate characteristics of SSTs (Supplementary Fig. 1a) and precipitation[18] (Supplementary Fig. 1b) observed during El Niño events were clearly evident. Although the response time of corals to ENSO was slightly different for SST and precipitation, a modern coral δ^{18}O record near the fossil coral site captured recent El Niño signals (Fig. 1; see Supplementary Information for a more detailed discussion). These findings suggest that our coral site and coral records were adequate for detecting ENSO events.

To decipher the seasonal and interannual characteristics of the Pliocene ENSO, we used two 35-yr δ^{18}O records with monthly resolution deduced from fossil *Porites* corals. We found these exceptionally well-preserved fossil corals in slightly separated stratigraphic levels of

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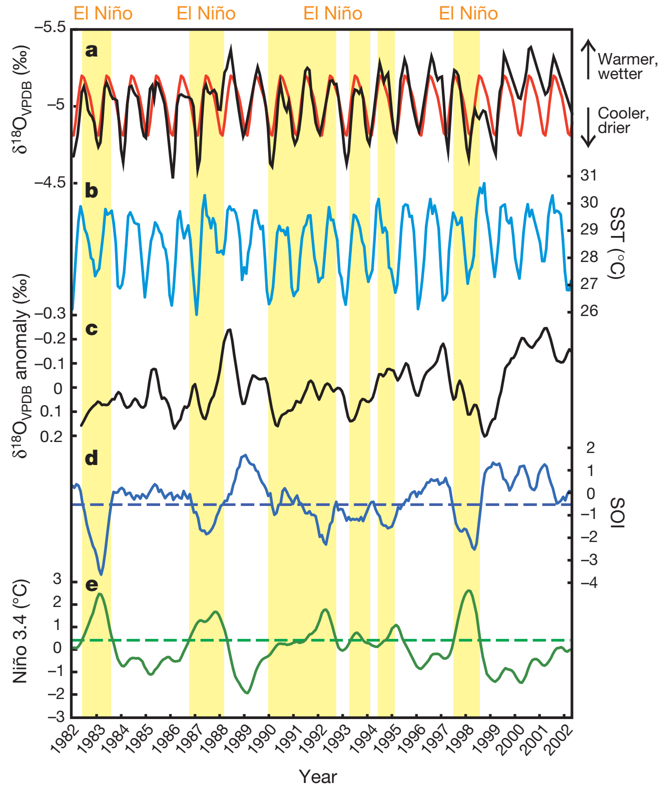

Figure 1 | Comparison of modern coral $\delta^{18}O$, local SST and coral $\delta^{18}O$ anomalies and ENSO proxy time series. Monthly resolution $\delta^{18}O$ time series (**a**; black) and climatology (**a**; red) are shown in comparison with monthly SSTs (**b**), modern coral $\delta^{18}O$ anomalies (**c**), the Southern Oscillation index (SOI; **d**) and the temperature anomaly in the Niño 3.4 region (**e**). ($\delta^{18}O = (^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1$; here the standard is Vienna PeeDee Belemnite (VPDB)). Monthly SST data came from the National Oceanic and Atmospheric Administration[23] (NOAA OI SST version 2). The yellow shading indicates the time periods of recent El Niño events, defined as those periods when the temperature anomaly in the Niño 3.4 region is above 0.5 °C (green dotted line) and/or the SOI is less than 0.5 (blue dotted line).

the Tartaro Formation on the island of Luzon in the Philippines (Supplementary Fig. 1a, b). Observation of nannofossil assemblages revealed the ages of the fossils to be approximately 3.5–3.8 million years (age determination was based on the occurrence of *Sphenolithus* spp. and the absence of *Reticulofenestra pseudoumbilicus*[19] (>7 μm)). For geochemical analysis, we selected well-preserved specimens from large coral colonies of *Porites* sp. from the coral boulders recovered.

Selected samples were examined to test for diagenetic alternation (Methods Summary and Supplementary Figs 2–4). Coral specimens containing no detectable altered mineral phases (corals 1 and 2) were used for detailed $\delta^{18}O$ measurements (Methods Summary and Supplementary Fig. 2). Selected colonies were cut into slabs (5 mm thick) parallel to the axis of maximum growth and X-rayed. The X-rays revealed distinct density band couplets (Supplementary Fig. 2). There were 35 distinct seasonal bands in each of the two time series (Fig. 2), and distinct attenuations in seasonal amplitudes were found in the $\delta^{18}O$ values for both PWP coral records. These attenuations also appeared in modern coral records during El Niño events in WPWP regions (Indonesia[15], Papua New Guinea[14], New Caledonia[15] and the Philippines; Fig. 1). The seasonal amplitudes of skeletal $\delta^{18}O$ values for coral 1 were significantly larger than those for coral 2, suggesting that these two coral colonies grew for different time periods during the PWP. These findings suggest that ENSO existed during different time windows within the PWP.

We calculated the power spectral densities for the two time series of anomalies from seasonal cycles for corals 1 and 2 (Fig. 3a), as well as those for a modern coral record (Fig. 3b) and for the temperature anomaly in the Niño 3.4 region over the same intervals (1950–1984 and 1985–2010, respectively; Fig. 3c). We also determined the average power spectrum for both time series (Supplementary Fig. 5 and Supplementary Information). Local peaks with a 3.5-yr period were commonly found in all spectra. Although the peak–trough contrast was relatively small for coral 1 and the individual spectra of corals 1 and 2 were different in character, such fractionation was also found in recent ENSO spectra (Fig. 3c) and in the reconstructed ENSO variability during the last millennium[20] and on the glacial–interglacial timescale[14]. The power spectral density of the PWP coral records suggests that ENSO-like interannual variability occurred over the tropical Pacific in the Pliocene period.

The early PWP (3–4.5 million years ago) has been widely studied as an analogue of future global climate changes that human beings will face in the coming decades. It is therefore crucial to determine the state of ENSO during the PWP and to predict how it will behave in the coming centuries in terms of strength and frequency. Until now, the characteristics of the interannual variability of ENSO during the PWP have been unknown. A recent modelling study[7] using a coupled ocean–atmosphere general circulation model has suggested that El Niño events occurred in the Pliocene. Our results provide the first proxy evidence of ENSO-like interannual variability occurring during the PWP. This direct evidence could be used to determine the mechanism underlying ENSO, to predict future climate behaviour, for example to assess how a warm climate affects the variability and amplitude of ENSO. Century-long coral records have been used to discuss the possibility that the strength of ENSO variability may depend on the

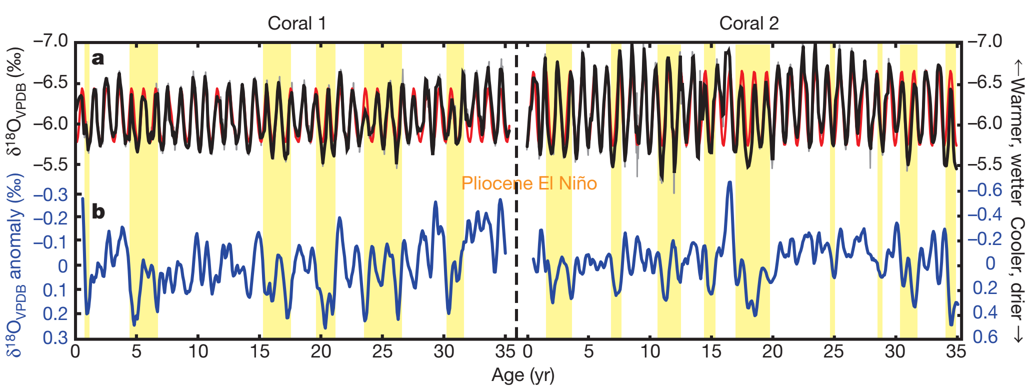

Figure 2 | Pliocene El Niño recorded in PWP oxygen isotopic records. a, Oxygen isotopic time series (black), best-fit climatology (red) and raw data plots (grey) for PWP corals (corals 1 and 2). Oxygen isotope records were interpolated to a resolution of 12 samples per year and climatology was calculated using annual and semi-annual sinusoidal functions. **b**, Anomalies in the PWP coral $\delta^{18}O$ time series ($\delta^{18}O$ minus climatology in **a**). The standard deviations of the anomalies were 0.139 for coral 1 and 0.217 for coral 2. The yellow shading indicates possible Pliocene El Niño events.

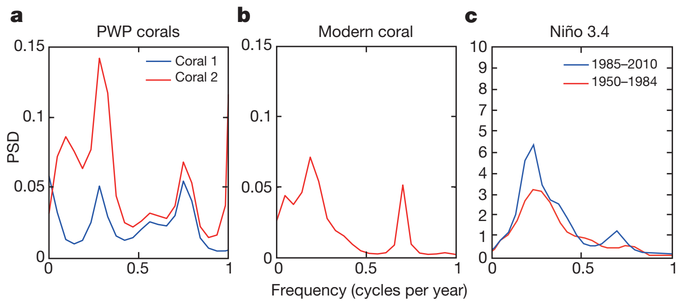

Figure 3 | Power spectral densities. Power spectral densities (PSDs) estimated by the maximum-entropy method for PWP fossil corals (**a**; blue, coral 1; red, coral 2), modern coral $\delta^{18}O$ (**b**) and the Niño 3.4 index (**c**; red, 1950–1984; blue, 1975–2010). A local peak at around 0.3 cycles per year is common to all of the spectra. This peak was statistically significantly larger than the trough at around 0.5 cycles per year at the 90% confidence level for coral 2. The peak–trough contrast was too small to be significant, however, for coral 1.

average conditions of factors such as SST[21]. Our PWP coral records suggest that the characteristics of the Pliocene ENSO were similar to those of recent ENSO events, and stand in contrast to studies suggesting that past and future warm climate background conditions will lead to a permanent El Niño state[1,6,8,9]. The present study reveals active ENSO dynamics resulting from the interannual variability of WPWP movements during the PWP, supporting the hypothesis that stronger winds in the tropical Pacific[22] act as a possible driving force behind ENSO when SSTs are higher than present levels[4]. This stronger wind enhanced by a heated ocean during the PWP probably led to a positive-feedback effect on ENSO dynamics, and such positive-feedback climate systems may occur in the future. That said, on the basis of millennium-long records of overlapping young and fossil corals it has been implied that the internal dynamics in the ENSO system itself might also cause the large and abrupt changes in ENSO characteristics even without external forcing[20]. ENSO might have a stronger or more frequent impact on climates in the mid to high latitudes in the future. Additional work is necessary to understand the role of the Pliocene El Niño on the teleconnection pattern in the Pacific Ocean during warm conditions.

METHODS SUMMARY

Screening methods for coral diagenesis. We screened and selected two exceptionally well-preserved fossil specimens for signs of diagenetic alternation using the following methods: (1) screening tests, including X-ray radiography and X-ray diffraction analysis, and (2) microanalysis of thin sections using the high-energy synchrotron X-ray diffraction analysis in combination with microstructural observation by scanning electronic microscopy and optical microscopic observation (see Supplementary Information for more detailed methods and discussion of diagenesis).

Oxygen isotope analysis. We performed microsampling along the major growth axis at 400-µm intervals. Microsamples of two coral cores (corals 1 and 2), which each weighed approximately 70–110 µg, were reacted with 100% H_3PO_4 at 90 °C in an automated carbonate preparation device coupled to a Micromass Optima mass spectrometer. Isotopic data are reported as per mil (‰) deviations relative to Vienna PeeDee Belemnite. The typical precision was better than 0.1‰ (see Supplementary Information for more details).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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