El Niño/Southern Oscillation and tropical Pacific climate during the last millennium

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Any assessment of future climate change requires knowledge of the full range of natural variability in the El Niño/Southern Oscillation (ENSO) phenomenon. Here we splice together fossil-coral oxygen isotopic records from Palmyra Island in the tropical Pacific Ocean to provide 30–150-year windows of tropical Pacific climate variability within the last 1,100 years. The records indicate mean climate conditions in the central tropical Pacific ranging from relatively cool and dry during the tenth century to increasingly warmer and wetter climate in the twentieth century. But the corals also document a broad range of ENSO behaviour that correlates poorly with these estimates of mean climate. The most intense ENSO activity within the reconstruction occurred during the mid-seventeenth century. Taken together, the coral data imply that the majority of ENSO variability over the last millennium may have arisen from dynamics internal to the ENSO system itself.

Despite recent advances in the understanding of the life cycle of the ENSO phenomenon—advances that have enabled climate models to forecast the evolution of an El Niño event with as much as six months lead time—many aspects of its physics remain unknown. Current ENSO theory holds that the growth and subsequent decay of El Niño events every few years is best explained with a recharge oscillator[1]. However, there is still no consensus on the origin of ENSO's observed irregularity[2], which has been attributed variously to the effects of random atmospheric noise[3,4], low-order chaos[5–7], and low-frequency climate fluctuations[8–10].

One of the largest uncertainties concerns the relationship between ENSO characteristics and changes in the background climate state, whether natural or anthropogenic. The occurrence of very strong El Niño events in 1982 and 1997 has intensified the debate surrounding ENSO variability. To some extent, successful long-term climate prediction rests on the issue of whether the unusual severity of these events was a consequence of rising global temperatures[11] or was simply representative of natural variability[12,13]. Numerical climate models provide few constraints: when charged with predicting how ENSO will change under continued greenhouse forcing, they yield a broad range of possible results[14–16]. Given that the mean state of the tropical Pacific climate system is known to vary over decadal to centennial timescales[17,18], and may be changing in response to continued greenhouse forcing[9,19], it becomes especially important to determine the natural range of tropical Pacific climate variability and the controls on this variability. Specifically, extended records of ENSO across a variety of background climate conditions are required to test ENSO theories and models.

Long-lived corals provide continuous, high-resolution reconstructions of tropical Pacific climate that supplement the instrumental record of climate from this key region. Modern coral records from the central tropical Pacific that extend several centuries rival the fidelity of the instrumental record during the twentieth century, and have yielded insights into the recent history of tropical Pacific climate variability on a variety of timescales[20–23].

More recently, researchers have turned to fossil corals (colonies that are not living at the time of collection) to probe the characteristics of the tropical Pacific climate system in the more distant past[24–26]. Two limitations have hampered the widespread development of this approach. First, compared to modern corals, which are ubiquitous throughout the tropics, fossil corals of any significant length are extremely rare, and thus it has been difficult to reproduce fossil-coral-based climate proxy records. Second, because fossil-coral records are typically several decades long, they probably underestimate the full range of tropical Pacific climate variability in a given period. Even so, fossil corals represent the most direct source of monthly resolved records of tropical Pacific climate before about AD 1600. This unique capacity prompts us to pursue methods that might overcome the limits of the archive.

Here we generate multi-century, monthly resolved records of tropical Pacific climate variability over the last millennium by splicing together overlapping fossil-coral records from the central tropical Pacific. These precisely dated, well-reproduced records allow us to characterize the range of natural variability in the tropical Pacific climate system with unprecedented fidelity and

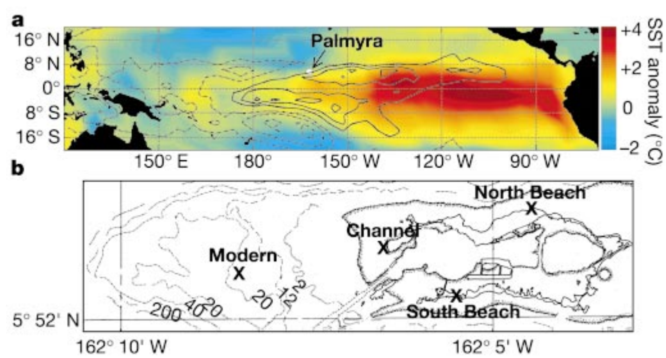

Figure 1 Maps of the study site. **a**, Map of the tropical Pacific showing location of Palmyra Island with respect to SST[45] (°C) and rainfall anomalies[46] (contour interval = 10 cm month^{-1}; solid (dashed) lines enclose positive (negative) anomalies) during the peak of the 1982–83 El Niño event. **b**, Map of Palmyra Island showing coral collection sites. Depth is contoured in metres. The modern coral was collected at the 'Modern' site, whereas the fossil corals were collected at the other three sites.

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detail. Collectively, the records document a wide range of ENSO characteristics, along with substantial decadal-scale variability and more subtle centennial-scale fluctuations in tropical Pacific climate over the last millennium.

Splicing together fossil-coral records

We apply oxygen isotopic analysis to a large collection of fossil corals from Palmyra Island (6° N, 162° W) to construct proxy records of tropical Pacific climate variability during the last millennium (see Supplementary Methods). Climate at Palmyra is dominated by ENSO variability, manifest as warmer, wetter conditions that persist during El Niño events and cooler, drier conditions during La Niña events (Fig. 1a). Positive sea surface temperature (SST) and rainfall anomalies that occur at Palmyra during an El Niño event both result in lowered (more negative) coral $\delta^{18}O$, while the converse is true during a La Niña event. Thus, Palmyra corals are sensitive recorders of regional-scale ENSO activity. For example, a $\delta^{18}O$ record from a modern coral (*Porites lutea*) at Palmyra shares 72% of its interannual variance with the NIÑO3.4 index (Fig. 2), demonstrating that coral records from this site provide reliable proxies of ENSO activity, at least over the twentieth century[23]. Our ability to reconstruct ENSO from fossil corals at this site rests in part on the assumption that the spatial patterns of ENSO have not changed significantly over the last millennium.

During two field excursions to Palmyra Island, we recovered dozens of 30–90-yr-long fossil-coral sequences from large, intact, *Porites* coral heads that were scattered on three different ocean-facing beaches (Fig. 1b). The Palmyra fossil-coral fields resemble storm-derived deposits that have been documented on other islands in the tropical Pacific[27], including nearby Christmas Island. The absence of extensive bioerosion in the Palmyra fossil corals supports the likelihood that wave activity from large, infrequent tropical storms transported the corals onto the beaches either before or shortly after their death, as the skeletons of dead corals are subject to rapid bio-erosion if they remain under water.

The numerous overlapping fossil coral sequences allow for the possibility of concatenating individual sequences that are detailed enough to resolve interannual variability into longer, well-reproduced sequences that span several centuries of tropical Pacific climate. High-precision, accurate U/Th dates (generally ±5–10 yr)[28] serve as guides for overlapping corals, but high coral-to-coral reproducibility of the $\delta^{18}O$-based climate proxy records is required to make a definitive match between coral $\delta^{18}O$ sequences.

We use a young fossil coral that overlaps the modern coral during the early twentieth century to test both the U/Th-dating accuracy and the fidelity of young fossil coral $\delta^{18}O$ records. Five U/Th dates from the young fossil coral suggest that the beginning of the fossil-coral sequence falls between AD 1900 and 1915 (ref. 28). A firm match between the modern and fossil coral $\delta^{18}O$ records occurs when the fossil coral starts at AD 1915 (Fig. 3). The $\delta^{18}O$ reproducibility between the modern and fossil coral is highest in the interannual band (the corals share 83% of their 2–7-yr variance). In other words, the fossil coral and the modern coral contain similar records of ENSO variability throughout the interval of overlap.

We apply the same approach to overlap three coral $\delta^{18}O$ records from the seventeenth century and five coral $\delta^{18}O$ records from the fourteenth and fifteenth centuries (Fig. 4a and b, respectively). Two to five U/Th dates from each coral support the multi-coral $\delta^{18}O$ composites shown in Fig. 4 (see Supplementary Fig. S1). As in the twentieth-century case, each set of overlapping corals contains similar patterns of interannual $\delta^{18}O$ variability (correlation coefficients for overlapping 2–7-yr bandpassed records range from 0.67 to 0.87). Together, the overlapping corals provide strong evidence that ENSO variability is the dominant source of $\delta^{18}O$ variability in the Palmyra fossil-coral $\delta^{18}O$ records.

With the exception of the fourteenth–fifteenth century corals, whole-coral $\delta^{18}O$ offsets for overlapping sets of corals are smaller than analytical uncertainty (±0.05‰, 1σ). However, the mean $\delta^{18}O$ values for the five overlapping corals from the fourteenth–fifteenth centuries are spread across a 0.3‰ range (Fig. 4b). Inter-coral offsets of up to 0.4‰ have been observed in neighbouring modern corals elsewhere in the central Pacific[29], and may reflect slight differences in the corals' microenvironments (water depth, sun exposure, circulation regime, and so on). Nonetheless, the range of offsets observed in the five fourteenth–fifteenth century fossil corals implies that there is a ±0.12‰ (1σ) (or ±0.5 °C, if scaled to temperature alone) error associated with reconstructing mean climate conditions from a single fossil-coral $\delta^{18}O$ record.

The splicing approach reduces this source of error by increasing the number of independent realizations of the climate state during a given time interval (assuming that mean coral $\delta^{18}O$ values are normally distributed about a value that represents the true climate state). Consequently, the error of our mean climate estimates for the twentieth century (based on two corals), the seventeenth century (based on three corals), and the fourteenth–fifteenth centuries (based on five corals) are all significantly less than ±0.12‰, the error for single coral estimates. However, this ±0.12‰ error does apply to two single fossil-coral $\delta^{18}O$ records from the tenth and twelfth centuries that comprise the earliest portions of the Palmyra reconstruction.

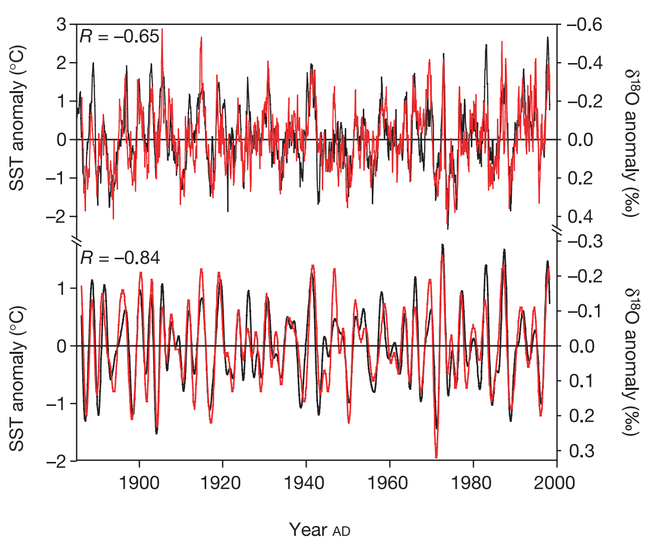

Figure 2 Comparison of coral-based and instrumental records of central tropical Pacific climate during the twentieth century. Top, Palmyra modern coral $\delta^{18}O$ anomalies (red; deseasoned, 30-yr highpass filtered) plotted with NIÑO3.4 SST anomalies (black; the average of SST anomalies from 5° N to 5° S, 120° W to 170° W)[47]. Bottom, same as top but a 2–7-yr bandpass filter has been applied to the records shown above.

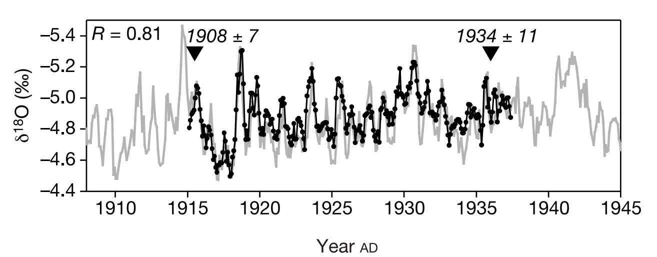

Figure 3 The $\delta^{18}O$ match between a young fossil coral from Palmyra (black) and the Palmyra modern coral (grey). Dating constraints for the fossil coral (in italics) come from multiple U/Th dates sampled from horizons marked by triangles[28].

The high degree of interannual reproducibility between the overlapping fossil-coral $\delta^{18}O$ records has two important implications for the reconstruction of tropical Pacific climate based on the Palmyra corals. First, it ensures that 'spliced' $\delta^{18}O$ records that are produced by joining the two longest coral $\delta^{18}O$ sequences at an arbitrary point can be viewed as continuous and accurate representations of climate variability. With current data, the splicing technique produces composite $\delta^{18}O$ records that are roughly twice as long as any given individual $\delta^{18}O$ record. Second, the inter-coral reproducibility lends credence to the interpretation of ENSO characteristics in individual fossil-coral $\delta^{18}O$ records, when overlapping corals are not available.

Tropical Pacific climate variability

We analyse the variability contained in monthly resolved coral $\delta^{18}O$ records from five intervals of the last millennium: AD 928–961, 1149–1220, 1317–1464, 1635–1703 and 1886–1998 (Fig. 5). The tenth- and twelfth-century sequences represent single fossil-coral $\delta^{18}O$ records, the fourteenth–fifteenth- and the seventeenth-century sequences are spliced fossil-coral $\delta^{18}O$ records, and the twentieth-century sequence is the modern coral $\delta^{18}O$ record.

Time-series analyses of the fossil-coral records reveal a range of ENSO frequencies and amplitudes exceeding that exhibited in the twentieth-century coral (Fig. 6a and b). For example, some seventeenth-century El Niño events rival the 1997 El Niño event in severity. ENSO activity in the seventeenth-century sequence is not only stronger (in terms of variance), but more frequent than ENSO activity in the late twentieth century. This conclusion holds for a variety of time-series analysis techniques, including spectral analysis and a range of different bandpass filters. On the other extreme, there are 30-yr intervals during both the twelfth and fourteenth centuries when ENSO activity is greatly reduced relative to twentieth-century observations. Taken together, the fossil corals portray a highly variable ENSO over the last millennium whose amplitude and frequency changed markedly, in some cases over the course of a decade.

The fossil-coral data allow for a critical assessment of several theories that have been proposed to explain ENSO variability. First, the data test the suggestion that changes in the mean state, whether through natural decadal-scale variability or greenhouse warming, may alter ENSO characteristics[10,11]. The relationship between ENSO variance and mean coral $\delta^{18}O$ is weak ($R = 0.43$), mostly because ENSO variance changed significantly while mean coral $\delta^{18}O$ remained relatively stable during the fourteenth–fifteenth centuries (Fig. 6a and c, and Supplementary Fig. S2). Overall, the corals resolve a broad range of ENSO variances that cannot be explained by changes in the mean state.

An alternative explanation for the observed irregularity of ENSO is that noise in the climate system, most likely of atmospheric origin, interferes with the recharge oscillator that is thought to set ENSO's periodicity[1,3,4]. If random noise is the dominant source of ENSO's variability, then ENSO indices should be stationary—that is, the statistics of the time series (its spectral properties and variance) should not change appreciably through time. However, two of the fossil-coral sequences—the records from the twelfth and the fourteenth–fifteenth centuries—exhibit significant changes in ENSO behaviour from decade to decade (Fig. 6a). A definitive test for non-stationary behaviour requires longer records than those available at present, but the coral records produced thus far suggest that large fluctuations in ENSO variance are fundamental to the physics

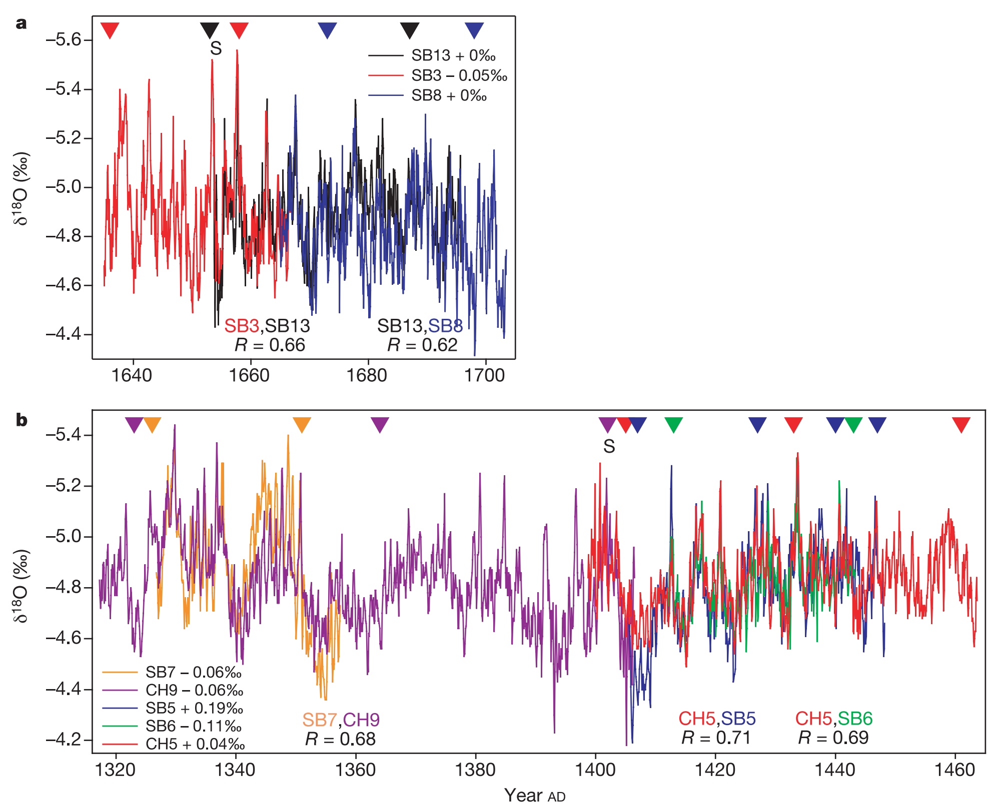

Figure 4 Overlapping fossil-coral $\delta^{18}O$ records. **a**, Three overlapping coral $\delta^{18}O$ records from the seventeenth century, shown with U/Th dating constraints (triangles; error is ±5–10 yr for single U/Th dates, ±5 yr for spliced record) and location of splice ('S'). The key reports the offsets in mean coral $\delta^{18}O$ that were applied prior to plotting. Correlation coefficients for sets of overlapping coral $\delta^{18}O$ records are shown along the bottom. **b**, Same as **a** but for five overlapping coral $\delta^{18}O$ records from the fourteenth–fifteenth centuries. Axis scalings for the two plots are identical. SB and CH designations refer to samples collected at the South Beach and Channel sites, respectively.

of the phenomenon.

In fact, the behaviour exhibited by the coral records is reminiscent of ENSO 'regime changes' that occur in a variety of ENSO models whose variability is partially a product of chaos[5–7,30]. The potential for regime-like changes in ENSO characteristics carries important implications for future climate changes under continued greenhouse forcing, because it allows for a nonlinear response of the global climate system to linear forcing.

Apart from ENSO variability, the Palmyra corals also resolve substantial decadal-scale variability that acts on a broad range of timescales from 8 to 30 yr. Power spectra of the records show no sign of a preferred periodicity for this low-frequency variability, which approaches a red noise continuum in the 150-yr-long sequence (not shown). However, it is clear from a comparison of Fig. 6a and c that decadal-scale variability is distinguishable from the decadal modulation of ENSO. This observation implies that the dynamics that underlie decadal-scale variability must be distinct from those of ENSO.

Given that coral $\delta^{18}O$ is a mixed SST and sea surface salinity signal, it is difficult to translate mean coral $\delta^{18}O$ into firm estimates of century-scale SST variability. However, if we assume that warmer SST is tightly coupled to anomalous convection in the central tropical Pacific on centennial timescales, as it is on interannual timescales, then the Palmyra corals provide unique constraints on the evolution of mean climate in the central tropical Pacific over the last millennium. Evidence for a tight SST–rainfall coupling on timescales longer than ENSO comes from the late-twentieth-century trend in coral $\delta^{18}O$. Recent estimates of central tropical Pacific warming since the 1970s are ~0.8 °C[19], which would correspond to a ~0.14‰ decrease in coral $\delta^{18}O$, using the SST/$\delta^{18}O$ calibration from Fig. 2. The actual change in the coral $\delta^{18}O$ over this time period is about −0.30‰, a roughly twofold amplification that must be ascribed, at least in part, to regional-scale freshening that accompanied central tropical Pacific warming. If twentieth-century SST–rainfall relationships apply throughout the last millennium, then the Palmyra fossil corals should be sensitive recorders of mean climate change in the central tropical Pacific.

That said, mean coral $\delta^{18}O$ values for the twelfth, fourteenth–fifteenth, seventeenth and early twentieth centuries vary within a relatively narrow 0.14‰ range (or 0.6 °C, if scaled to temperature alone). The only significant departures in mean coral $\delta^{18}O$ occur in the tenth century and late-twentieth-century sequences. It seems probable that the tenth century witnessed the coolest and/or driest conditions in the central tropical Pacific of the last 1,100 years, although this conclusion must be verified by additional tenth-century coral records. The late twentieth century, the period covered by dense instrumental climate data, represents the warmest, wettest interval of the last millennium.

Proxy–proxy comparisons

To build a complete interpretive framework for the Palmyra coral reconstruction, it would be necessary to compare the Palmyra fossil-coral ENSO results with proxy records of tropical Pacific origin that span the last millennium. Currently, multi-proxy reconstructions of tropical Pacific SST that extend back as far as the seventeenth century are the most likely candidates[31–33], but the earliest portions of these records are associated with large errors that render comparisons with the Palmyra corals questionable.

In lieu of high-resolution proxy records of tropical Pacific climate, we compare the Palmyra corals to reconstructions of Northern Hemisphere temperature that span the last millennium. The Mann *et al.*[34] multi-proxy reconstruction (hereafter MBH) is representative of most of the proxy-based Northern Hemisphere temperature reconstructions in that it broadly defines centuries of relatively warm and cool conditions, the 'Medieval Warm Period' (MWP) and the 'Little Ice Age' (LIA), respectively (Fig. 5). Crowley[35] reproduced several key features of the MBH reconstruction by combining volcanic and solar forcing in an energy-balance climate model. Solar irradiance changes have been linked to century-scale climate variability in a variety of tropical proxy records[36,37], while

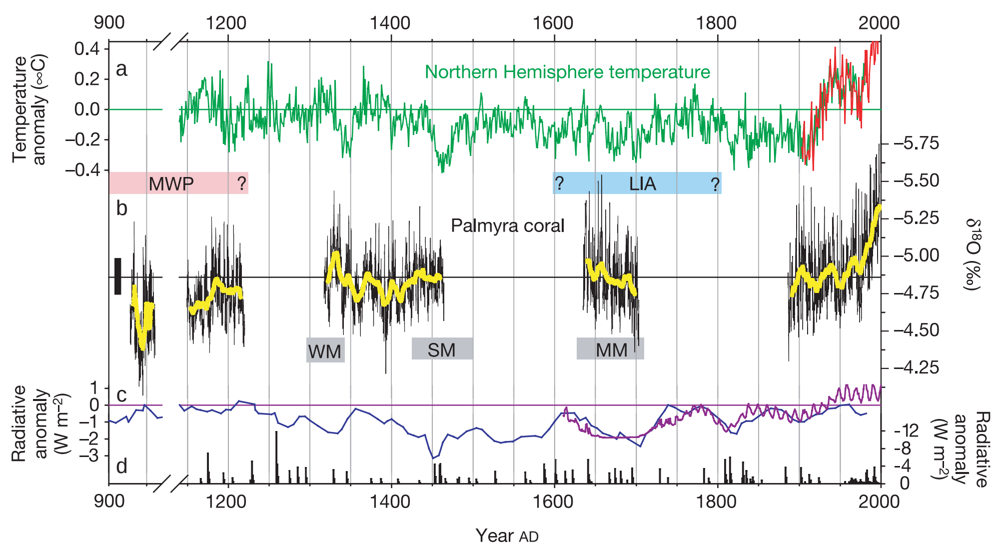

Figure 5 Comparison of proxy climate records and external forcing during the last millennium. **a**, The MBH Northern Hemisphere temperature reconstruction[34] (green) plotted with the Northern Hemisphere instrumental temperature record of ref. 48 (red). The green horizontal line denotes the mean of the MBH record for the period AD 1886–1975. **b**, The monthly resolved Palmyra coral $\delta^{18}O$ records (thin black line), shown with a 10-yr running average (thick yellow line). The black horizontal line represents the average of the Palmyra modern coral $\delta^{18}O$ for the period AD 1886–1975. The black vertical bar represents the $\pm 1\sigma$ error in mean coral $\delta^{18}O$ for single fossil corals (this error applies only to tenth- and twelfth-century sequences). The dating error is ±10 yr for the tenth- and twelfth-century sequences, ±5 yr for the fourteenth–fifteenth- and seventeenth-century sequences, and ±<0.5 yr for the twentieth-century sequence. **c**, Reconstruction of solar irradiance anomalies based on historical sunspot records (anomalies calculated with respect to the AD 1886–1975 mean)[49] (purple) plotted with ^{10}Be anomalies (a proxy for solar activity)[50] (blue), plotted as a 3-point running mean and scaled to the solar irradiance anomalies. **d**, Radiative forcing associated with volcanic eruptions recorded in ice cores (black)[35]. The approximate timing and duration of the 'Little Ice Age' (LIA), the 'Medieval Warm Period' (MWP), and solar activity minima—the Maunder minimum (MM), the Spörer minimum (SP), and the Wolfe minimum (WM)—are marked by horizontal bars.

large volcanic eruptions have a measurable cooling effect on global average temperature[38]. The links between the tropical Pacific climate system and solar (or volcanic) forcing over the last millennium are less clear. The combination of decreased irradiance and increased volcanism in the seventeenth century apparently did not result in strong immediate cooling of the central tropical Pacific. Likewise, increased irradiance and decreased volcanism did not result in immediate warming of the central tropical Pacific during the MWP. Furthermore, close inspection of the data (Fig. 5c and d versus Fig. 6) reveals little decadal-scale correspondence between the Palmyra reconstruction and the implied solar or volcanic forcing, either in terms of ENSO characteristics or variability in the mean state.

On the other hand, it can be argued that the east–west difference in SST across the tropical Pacific, not average SST, is a key determinant for global climate patterns. The Palmyra coral data, in combination with a handful of ENSO-sensitive proxy records, do suggest that the Pacific's zonal SST gradient may have been larger during the MWP and smaller during the LIA. Higher mean δ^{18}O values in the tenth- and twelfth-century Palmyra corals hint at relatively cool and/or dry mean climate conditions in the central tropical Pacific, states that are both consistent with La Niña-like conditions. Cool conditions in the central tropical Pacific may have played a role in the severe, prolonged drought that lowered lake levels in Meso-America, the Sierra Nevada and Kenya[39–41] early in the millennium, because central tropical Pacific cooling is typically associated with anomalously dry conditions in these areas during La Niña events[42]. Evidence for increased river runoff at about AD 1000 in northern South America[43], an area in which precipitation increases during La Niña events, also supports the inference of an increased Pacific zonal SST gradient during the MWP.

More direct evidence of tropical Pacific climate is available for the seventeenth century, when the Palmyra corals register the most intense ENSO activity of the reconstruction with little change in mean climate conditions. During this time, western Pacific corals document cooler, drier conditions[18,44] while river discharge off northern South America decreased[43]. Both observations are consistent with a reduction in the tropical Pacific's zonal SST gradient, and in that sense may be related to the frequent, intense El Niño events recorded in the Palmyra corals during the seventeenth century.

The most striking difference between the Palmyra reconstruction and the reconstructions of Northern Hemisphere temperature is the pattern of twentieth-century climate change, specifically the timing and structure of the warming trend. There are no *a priori* reasons to doubt the accuracy of either record—there are abundant instrumental data from the Northern Hemisphere extending to AD 1900, and while this is not the case for the central tropical Pacific, the salient features of the Palmyra modern coral δ^{18}O trend are reproduced in other modern coral δ^{18}O records[21,22] from the central tropical Pacific. The mechanisms that are responsible for the stability of central tropical Pacific climate in the face of a ~0.4 °C increase in Northern Hemisphere temperature during the early twentieth century may help explain why average central tropical Pacific climate remained relatively stable over the last millennium. On the other hand, the accelerated warming that took place in the central tropical Pacific during the late twentieth century implies very different forcing and response, in all probability related to the rise in greenhouse gases.

In summary, the Palmyra corals could provide critical tests of numerical climate models that are charged with predicting future climate change. Currently, such models are geared toward reproducing twentieth-century climate variability. Both short- and long-term predictions may probably improve if models could also reproduce the variability exhibited by the Palmyra fossil corals through the different boundary conditions of the last millennium. Perhaps most relevant in this respect is the fact that ENSO characteristics apparently changed quite markedly over the course of ten years, even in the absence of obvious external forcing. Therefore, it is appropriate to consider that similarly large, abrupt

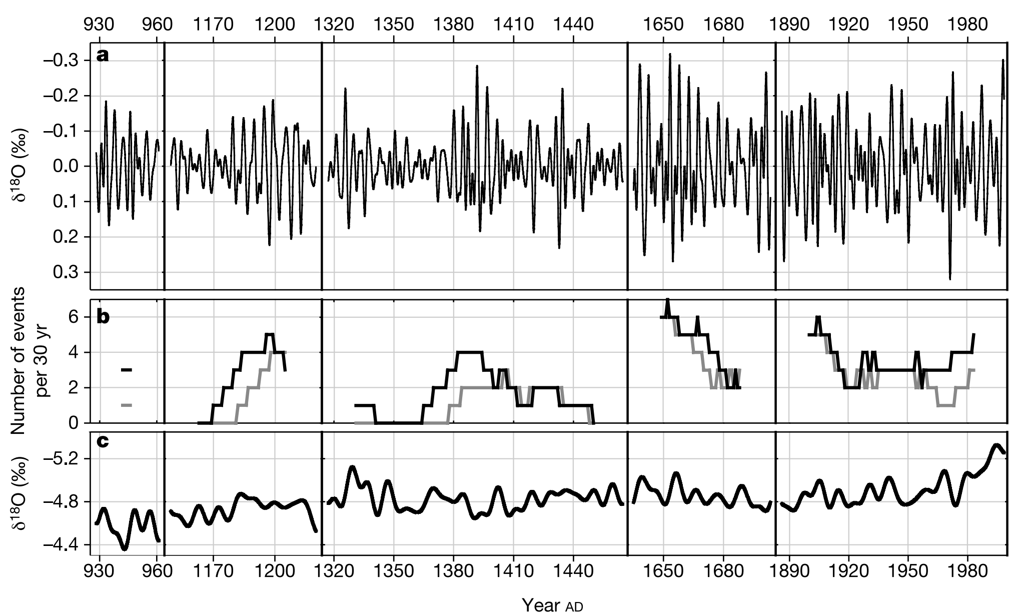

Figure 6 ENSO and lower-frequency components of the Palmyra coral δ^{18}O records. **a**, ENSO variability isolated by applying a 2–7-yr bandpass filter to the deseasoned monthly coral δ^{18}O anomaly data, plotted contiguously. **b**, An index of ENSO activity, defined as the number of El Niño (black) and La Niña (grey) events in a sliding 30-yr window. An El Niño (La Niña) event is defined by annual-mean δ^{18}O anomalies (computed from the 2–7-yr bandpass filter series, centred on January) that are less than (greater than) −0.11‰ (+0.11‰). This threshold corresponds to one standard deviation of the modern coral's 2–7-yr bandpassed record, and is roughly equivalent to NIÑO3.4 SST anomalies of 0.6 °C, according to the calibration presented in Fig. 2. **c**, Lower-frequency climate variability isolated by applying an 8-yr lowpass filter to the coral δ^{18}O data.

changes in the character of tropical Pacific climate variability may occur in the future, with or without a trigger from continued greenhouse forcing. □

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