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Coral record of reduced El Niño activity in the early 15th to middle 17th centuries

Kelly A. Hereid[1,2]*, Terrence M. Quinn[1,2], Frederick W. Taylor[2], Chuan-Chou Shen[3], R. Lawrence Edwards[4], and Hai Cheng[4]

[1]Department of Geological Sciences, Jackson School of Geosciences, University of Texas, Austin, Texas 78712, USA
[2]Institute for Geophysics, Jackson School of Geosciences, University of Texas, Austin, Texas 78758, USA
[3]High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, Republic of China
[4]Minnesota Isotope Laboratory, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455, USA

ABSTRACT

El Niño–Southern Oscillation (ENSO) powers global interannual climate variability through changes in trade wind strength, temperature and salinity anomalies, sea level, and atmospheric circulation patterns. ENSO variability is well characterized in modern times, but instrumental records cannot fully describe natural ENSO variability due to the imprint of anthropogenic climate forcing. ENSO activity may also be affected by solar variability, but the response of ENSO to such changes is difficult to predict. We constructed a continuous, monthly resolved, spliced fossil *Porites* coral $\delta^{18}O$ and Sr/Ca record from Misima Island, Papua New Guinea, in the Western Pacific Warm Pool, spanning 233 yr (1411–1644 CE [Common Era]). The Misima coral record indicates that the surface ocean in this region experienced a small change in hydrologic balance with no change in temperature, extended periods of quiescence in El Niño activity, and no change in average amplitudes of El Niño events relative to signals captured in regional modern records. The reduced El Niño variability occurs during a known change in solar forcing, the initiation of the Little Ice Age. However, there is no clear relationship between the timing of changes in solar forcing and ENSO activity, implying that ENSO variability changes arise from internal dynamics. The century-scale switch between active and inactive El Niño states has not previously been recorded, and provides a new baseline for climate models and reconstructions.

INTRODUCTION

The response of the tropical climate system to decreased solar forcing is debatable. The most recent period of reduced solar forcing is the Little Ice Age (LIA), ca. 1450–1850 (Steinhilber et al., 2009); some tropical paleoclimate records show LIA cooling (Thompson et al., 1995), but others indicate negligible temperature change (Hendy et al., 2002). Sediment and speleothem records suggest that a century-scale southward displacement of the Intertropical Convergence Zone and a weakened Asian Monsoon resulted in significant hydrologic reorganization during this interval (Oppo et al., 2009; Tierney et al., 2010; Zhang et al., 2008). The paleoclimate record of interannual variability is also unclear; records placing high levels of El Niño–Southern Oscillation (ENSO) activity during the LIA (Cobb et al., 2003) contrast with others where ENSO variability peaks during the Medieval Climate Anomaly (Moy et al., 2002).

Pre-industrial paleoclimate records can characterize the long-term response of ENSO variability to known natural perturbations in external forcing, providing an observational framework to inform predictions of the ENSO response to future climate change. This study assesses pre-industrial ENSO variability in the tropical western Pacific using a spliced, centennial-scale record (233 yr) of monthly resolved coral-inferred sea-surface temperature (SST) and salinity (SSS) during the early 15th to middle 17th centuries, a period coincident with the onset of the LIA (Steinhilber et al., 2009). We utilize oxygen isotope data ($\delta^{18}O$) as a combined proxy for SST and SSS (Cole et al., 1993; Evans et al., 2000), and Sr/Ca for age modeling and to constrain SST changes (Corrège, 2006). This multi-proxy approach separates hydrologic changes from long-term temperature trends.

Misima Island, Papua New Guinea (10.6°S, 152.8°E), lies at the southern edge of the Western Pacific Warm Pool (WPWP), an ocean region characterized by the warmest open-ocean surface temperatures, making it a major heat and moisture source to the climate system. The WPWP experiences cool (warm) and dry (wet) conditions during El Niño (La Niña) events (Rasmusson and Carpenter, 1982; Ropelewski and Halpert, 1987), and exhibits the ocean's largest SSS response to ENSO variability (Delcroix et al., 2011) (Fig. 1). Regional precipitation and temperature anomalies during ENSO events have an additive effect on $\delta^{18}O$ in coral aragonite: large positive (negative) excursions in $\delta^{18}O$ represent El Niño (La Niña) events (Quinn et al., 2006; Tudhope et al., 2001). We assess ENSO variability at Misima by calculating ENSO frequency and amplitude changes during the early 15th to middle 17th centuries, filling in a critical data gap in high-resolution pre-industrial climate records.

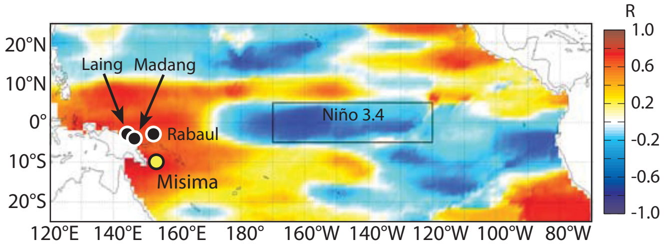

Figure 1. Map showing study location (Misima Island, Papua New Guinea) and correlation (R) between Niño 3.4 sea-surface temperature (SST) anomalies and Pacific sea-surface salinity (SSS) anomalies (Delcroix et al., 2011) in December of known El Niño event years, when central Pacific SST anomalies are largest. Yellow circle denotes location of Misima, and black circles indicate other modern coral records used in this study. Niño 3.4 region (black box) is a standard El Niño–Southern Oscillation (ENSO) index region. Strong positive correlation in the Western Pacific Warm Pool (WPWP) (R = 0.78 at Misima) indicates increases in salinity as the central Pacific warms.

METHODS

Fossil and near-modern *Porites* coral heads were cored in beach storm deposits at Misima. Three-inch–diameter cores were cut into 5 mm slabs and analyzed for diagenetic alteration using X-radiographs (Fig. DR1 in the GSA Data Repository[1]) and scanning electron microscopy. Slabs that did not show alteration were micromilled along the maximum growth axis

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*E-mail: hereidk@utexas.edu.

[1] GSA Data Repository item 2013020, monthly resolved coral geochemical data, and band-pass filtered coral geochemical data, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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at approximately monthly resolution using a computer-assisted drilling stage. The data were linearly resampled to 12 samples per year. A composite time series was created using two spliced fossil cores.

Analytical precision is 0.05‰ for δ^{18}O, and 0.02‰ for δ^{13}C (1σ, n = 393), with between-colony δ^{18}O uncertainty of 0.12‰ (Fig. DR2). Analytical precision for Sr/Ca ratios is 0.015 mmol/mol (1σ), with between-colony uncertainty of 0.062 mmol/mol (1σ). Raw Sr/Ca measurements were corrected using internal standards (Schrag, 1999). The geochemical age model was shifted within error of the ^{230}Th dates (Table DR1) to match the timing of the 1578 CE El Niño event known from historical records (Ortlieb, 2000).

A band-pass filter applied to the coral time series (Fig. 2) highlights variability at ENSO time scales (2–8 yr). The filtered data error of ±0.026‰ (1σ) was determined using a Monte Carlo analysis of 1000 synthetic data sets consisting of the original data set with random, normally distributed inter-colony error added. A band-pass filter was applied to each synthetic data set; the average standard deviation at each data point reflects the uncertainty. Similarly, threshold uncertainty was estimated by calculating the threshold on 1000 synthetic filtered data sets with error included.

RESULTS

A significant median shift in coral δ^{18}O (–0.27‰, $p < 0.0001$) between the fossil and near-modern Misima corals suggests warmer and/or fresher sea surface conditions in the early 15th to middle 17th centuries relative to the 20th century. The trend toward more negative isotopic values in modern times is observed in many coral records across the Pacific (Cobb et al., 2003; Hendy et al., 2002; Kilbourne et al., 2004). A portion of this shift at Misima may be due to intercolony variability, caused by local environmental variations (Linsley et al., 1999), but the deep thermocline and stable stratification in the WPWP tends to dampen upper-water-column variability (Lukas and Lindstrom, 1991). If this offset is due to regional climate trends, this finding is consistent with instrumental records indicating the WPWP is warming and/or freshening in response to climate change (Cravatte et al., 2009; Singh and Delcroix, 2011). The similar mean Sr/Ca values in the near-modern and fossil coral records imply little change in SST (Fig. DR3), favoring the interpretation of a freshening trend as the mechanism driving coral δ^{18}O changes. However, instrumental SST data indicate that this region has warmed slightly since the period when the coral grew (28.18 °C during the coral growth period, 28.50 °C in the most recent corresponding period, HadISST1.1). Furthermore, the annual cycle is significantly larger in the near-modern than in the fossil coral δ^{18}O record (0.39‰ and 0.25‰, respectively; $p = 0.0096$), but statistically equivalent between the near-modern and fossil Sr/Ca records (0.119 mmol/mol and 0.104 mmol/mol, respectively; $p = 0.3581$), again suggesting a change in hydrology rather than a change in SST as the primary driver of the coral δ^{18}O variations.

The acquisition of a modern century-scale coral record from Misima would be ideal, but has proven to be logistically unfeasible. Instead, the available near-modern Misima record was compiled with published Papua New Guinea coral records (Fig. 1) to develop a modern calibration data set (Fig. DR4; Table DR2). Papua New Guinea records capture the full range of 20th century multidecadal ENSO variability (Quinn et al., 2006; Tudhope et al., 2001) and have a similar SSS response to ENSO events (Delcroix et al., 2011), making them suitable for direct century-scale comparisons with the fossil record at Misima. These regional records allow more suitable comparisons than the longer Palmyra fossil record, whose differing ENSO sensitivity limits comparisons between the two regions (Fig. DR5). The Madang, Laing, and Rabaul coral records have significantly greater interannual variance than the Misima fossil record ($p < 0.0001$). The reduced interannual variability in the fossil Misima record relative to the century-scale modern Papua New Guinea records suggests that ENSO was less active during the early 15th to middle 17th centuries.

DISCUSSION

To quantify variability changes using individual ENSO events, we compared each modern coral δ^{18}O record with the instrumental Niño 3.4 record to empirically determine a threshold at which most ENSO events are captured, while minimizing incorrectly recorded events. To set the threshold for El Niño and La Niña events, we used a band-pass filter to remove long-term trends in individual records, and then incrementally changed the threshold level in steps of 0.01‰. At each step, we recorded the number of accurately identified ENSO events, as well as the number of errors for each record, and set the ENSO event threshold where the sum of all errors is minimized. We modeled changes in error range with record length to calibrate the error to the length of the fossil record. From this analysis, we set a threshold for Misima El Niño events at a 0.11 ± 0.03‰ anomaly (Fig. 2). The thresholds for La Niña events in this region are inflated by high rates of false positives (local, non-ENSO events); therefore, we interpret changes in only El Niño variability from Papua New Guinea coral records. The accuracy rates for modern records from Laing and Madang are equivalent within error to the near-modern Misima

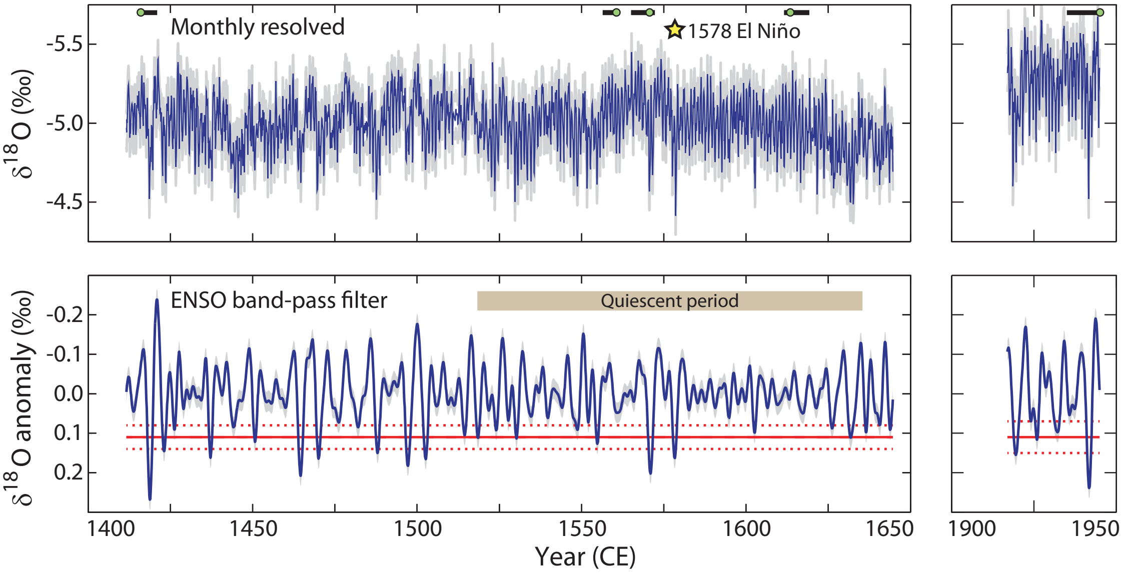

Figure 2. Coral-based El Niño reconstruction at Misima, Papua New Guinea. Monthly resolved and band-pass–filtered Misima δ^{18}O records for fossil (left) and modern (right) corals are shown. Age model is constructed using ^{230}Th dates (green circles) that have been shifted within error (black lines) to align with the known 1578 CE (Common Era) historical El Niño event (yellow star). Sections of filtered record that fall below the empirical El Niño event threshold (red line) (±1σ, red dotted line) correspond to El Niño events. Error range (gray shading) reflects replication error (1σ). El Niño–Southern Oscillation (ENSO) quiescence begins in early 1500s and extends through early 1600s.

record, but the accuracy at Rabaul does not overlap the near-modern Misima record, so it is excluded from further discrete event capture analyses.

We applied the empirically determined El Niño threshold to the fossil Misima record. Fifteen El Niño events (10–25, ±1σ) are observed over the 233 yr fossil record. Using the same analysis, we found 15 El Niño events (10–22, ±1σ) in the Madang record, 21 (16–24, ±1σ) at Laing, and 3 (2–4, ±1σ) in the near-modern Misima record (Table DR3). We compare the fossil and modern records directly using 100 yr running windows to count events (Fig. 3). Events in the fossil record drop to as few as 3 El Niño events (2–6, ±1σ) per century, below the minimum event counts per century at Madang and Laing. The 117 yr period between 1519 and 1636 CE contains fewer El Niño events per century than any century-long window in the modern Madang and Laing records. The fossil record also has a significantly lower number of total El Niño events than the century-scale modern records ($p = 0.0008$). The event number reduction does not represent a shift in the recurrence interval of El Niño events, but rather reflects long periods when the coral record experiences substantially reduced El Niño activity. The extended periods of quiescence in the late 16th and early 17th centuries drive an overall reduction in El Niño variability during this time, while the earlier section of the record contains a number of El Niño events comparable to modern times (Fig. 3).

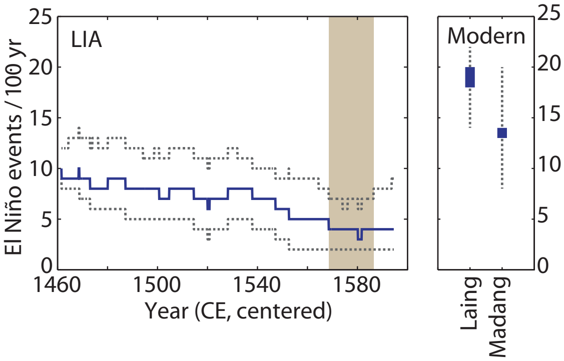

Figure 3. El Niño event reconstruction, showing 100 yr running count of El Niño events (defined by empirical isotopic event threshold, 0.11‰ ±0.03‰) in Little Ice Age (LIA) Misima (Papua New Guinea) record (blue line; year given is window center) compared with running 100 yr segments of modern coral records (blue rectangles) (Tudhope et al., 2001). Dashed gray lines reflect uncertainty in event counts due to replication error (±1σ). Locations of modern coral records are shown in Figure 1. Although the earliest part of the Misima record is comparable to modern records in events per century, the number of events per century declines precipitously during the 1500s CE (Common Era). The period 1519–1636 CE (centered on brown bar) has fewer events per century than any time in the modern Papua New Guinea records.

To quantify event magnitude changes, we calculated the amplitude peak for each El Niño event that crossed the event threshold for Madang, Laing, and Misima. We pooled the modern records and compared their magnitudes with the fossil record magnitudes. The modern median event size is 0.16‰ (0.14–0.19‰, 95% confidence interval), which is statistically equivalent ($p = 0.98$) to the fossil median event size of 0.16‰ (0.14–0.18‰, 95% confidence interval). This evidence shows that substantial changes in El Niño variability can occur even when event magnitudes remain consistent.

The reduced El Niño activity during the LIA at Misima could be explained two ways: either total ENSO variability in the Pacific was reduced in this interval, or there was an increase in La Niña events relative to El Niño events. Using only this WPWP record, we are unable to determine which of these scenarios is most likely, because this location is not expected to strongly record La Niña events. Therefore, we compared the Misima record with the TexMex tree ring reconstruction of Niño 3 (D'Arrigo et al., 2005), which has a high-skill, balanced El Niño and La Niña response (63% El Niño / 67% La Niña). To assess the relative strength of El Niño versus La Niña events, we calculate a 30 yr running mean of the ratio of El Niño to La Niña event numbers.

This record captures a broad decline in the proportion of El Niño events centered near 1600 CE (Fig. 4). Based on this analysis, we cannot exclude an increase in the proportion of La Niña events relative to El Niño events as a possible explanation for the decline in El Niño events at Misima.

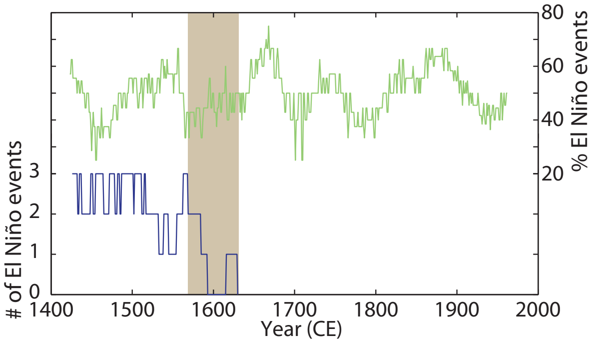

Figure 4. Relative contributions of El Niño versus La Niña events to El Niño–Southern Oscillation (ENSO) signal. Green line (top) shows the percentage ratio of El Niño to La Niña event rates over a 30 yr running window in a tree ring reconstruction of Niño 3 (D'Arrigo et al., 2005). The 30 yr running count of El Niño events at Misima (Papua New Guinea) (blue line) declines during a relative minimum in the contribution of El Niño events to the total ENSO signal (brown bar). The decline in El Niño events at Misima therefore may be driven by either a decline in total ENSO variability or an increased proportion of La Niña events.

Two competing hypotheses predict how ENSO variability reacts to a change in forcing. Previous studies suggested that extended periods of low ENSO variability could reflect a La Niña–like state, with a high zonal gradient in the Pacific damping the initiation of El Niño events (Mann et al., 2005). The response to an decline in solar input is offset by reduced upwelling in the eastern equatorial Pacific (Clement et al., 1996), causing a decrease in zonal Pacific SST gradient that is directly related to solar forcing, which favors El Niño event initiation (Emile-Geay et al., 2007). This effect is countered by increased zonal atmospheric circulation and deepening of the WPWP thermocline in response to cooling (Vecchi and Soden, 2007), so it is not clear which process would dominate. These two viewpoints may not be reconcilable within the limited time frame of models or the instrumental record, as the time required for the ENSO system to respond to a change in mean state is on the order of several centuries (Stevenson et al., 2012; Wittenberg, 2009). The reduced El Niño activity over the period of reduced solar forcing in the fossil Misima record appears to support the latter hypothesis, but a direct comparison with solar variability suggests that solar forcing alone is inadequate to explain multidecadal changes in interannual variability (Fig. DR6). Rather, multidecadal variability changes in the Misima fossil coral record fall within the range of unforced internal variability predicted by modeling studies (Wittenberg, 2009). Additional long, annually resolved paleoclimate records are essential to assess more realizations of changes in incoming solar radiation and determine how mean state changes influence ENSO variability.

CONCLUSIONS

The multi-century fossil record of El Niño variability at Misima suggests sizeable El Niño system changes during a period of tropical hydrologic changes in the early 15th to middle 17th centuries. The change in the mean and amplitude of the annual cycle in coral $\delta^{18}O$, without attendant Sr/Ca changes, is consistent with the concept that the WPWP underwent small but significant salinity changes without a corresponding change in SST between the early 15th to middle 17th centuries and modern times. The reduction of interannual variability depicts a climate state in which El Niño variability was significantly reduced relative to modern times, which occurs despite equivalent El Niño event magnitudes. This altered variability reflects periods of El Niño quiescence interspersed with times when El Niño variability approaches modern conditions, with no clear connection to solar forcing. This study demonstrates that significant changes in interannual variability are possible despite only minimal changes in mean climate state as a result of unforced internal variability.

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