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Sea surface temperature variability in the southwest tropical Pacific since AD 1649

Kristine L. DeLong[1]*†, Terrence M. Quinn[2,3], Frederick W. Taylor[2], Ke Lin[4] and Chuan-Chou Shen[4]*

A prime focus of research is differentiating the contributions of natural climate variability from those that are anthropogenically forced, especially as it relates to climate prediction[1-3]. The short length of instrumental records, particularly from the South Pacific, hampers this research, specifically for investigations of decadal to centennial scale variability[1,4]. Here we present a sea surface temperature (SST) reconstruction derived from highly reproducible records of strontium-to-calcium ratios (Sr/Ca) in corals from New Caledonia to investigate natural SST variability in the southwest tropical Pacific from AD 1649–1999. Our results reveal periods of warmer and colder temperatures of the order of decades during the Little Ice Age that do not correspond to long-term variations in solar irradiance or the 11-year sunspot cycle. We suggest that solar variability does not explain decadal to centennial scale SST variability in reconstructions from the southwest tropical Pacific. Our SST reconstruction covaries with the Southern Hemisphere Pacific decadal oscillation[5] and the South Pacific decadal oscillation[6], from which SST anomalies in the southwest Pacific are linked to precipitation anomalies in the western tropical Pacific[6]. We find that decadal scale SST variability has changed in strength and periodicity after 1893, suggesting a shift in natural variability for this location.

Shifts in Pacific Ocean SST on decadal to centennial timescales are a source of natural variability that has wide-ranging climatic consequences on fisheries and natural systems[3,7]. One particular mode of Pacific decadal variability (PDV) is the Pacific decadal oscillation (PDO) defined for the North Pacific[7] and the closely related basin-wide interdecadal Pacific oscillation[8,9] (IPO), both of which have periods of 20–30 years. Recent investigations[5,6,10] reveal a separate mode of PDV in the South Pacific defined as the Southern Hemisphere Pacific decadal oscillation (SHPDO; ref. 5) or South Pacific decadal oscillation (SPDO; ref. 6) that varies on 10–20-year timescales. These PDV modes are defined using interpolated SST databases[11,12] based on instrumental readings from historical nautical records, primarily from coastal locations (Supplementary Fig. S1), resulting in uneven areal coverage that should be accounted for in analyses of SST variability[4]. These SST databases include adjustments for observational bias such as corrections for bucket and engine intake measurements[4,11]. A recent study discovered an uncorrected instrumental bias in nautical records that is manifested as a shift to colder temperatures in 1945 (ref. 13). This bias coincides with a phase shift in the PDO (refs 3,7); however, the implications of this bias are unclear until the SST databases can be updated. Furthermore, these databases are temporally limited to the satellite era (1981–present)[12] for most of the South Pacific[4] (Supplementary Fig. S1) thus limiting our understanding of SST and surface ocean variability on longer timescales.

A way to overcome limitations in instrumental data is to develop high-resolution (monthly to annual) palaeoclimate proxies, particularly those that extend beyond the instrumental period[14–17]. One such record of oxygen isotope ratios (δ^{18}O) extracted from a coral in New Caledonia in the southwest tropical Pacific contains decadal scale variability (14–15 years; ref. 14), similar to the SHPDO and SPDO. Coral δ^{18}O vary with SST and the δ^{18}O of sea water, which varies with surface hydrologic processes or salinity; therefore, a more direct proxy of temperature is desired. A study of Sr/Ca determinations from corals, a direct proxy for temperature, compared these determinations with interpolated SST databases and found that these databases do not accurately resolve the amplitude of decadal scale climate variability[15]. High-quality palaeoclimate records, such as the one presented here, are required to address these differences.

Here we present 350 years of reconstructed monthly SST derived from the Sr/Ca variations of two cores from a coral colony in New Caledonia for which the chronology is absolutely dated (Figs 1 and 2). We established our chronology using a cross-dating method[15] confirmed with high-precision thorium-230 (^{230}Th) dating[18]. This reconstruction was calibrated and verified with *in situ* SST and regional SST records in previous studies[15,19] that demonstrated the coral Sr/Ca variations captured SST variability (Fig. 2b; maximum 52% of variance in SST anomaly (SSTA), Table 1) with no dependence on salinity. We examined the sources of uncertainty by comparing coral Sr/Ca records within the same colony and between colonies. We found ~45% of the regression error is caused by assigning any one sample to a particular month, thus regression error decreases for timescales greater than subannual (Supplementary Table S1). Therefore, we smoothed the reconstruction to minimize subannual dating uncertainties and to highlight interannual variability. We assessed the reconstruction error based on the number of cores and for different methods of smoothing (Fig. 2 and Supplementary Table S1). All temperatures are reported as departures from the average monthly temperature for the interval from 1961 to 1990 (Figs 2 and 3; annual cycle = 5.0 °C), similar to the Intergovernmental Panel on Climate

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[1]College of Marine Science, University of South Florida, 140 7th Avenue South, St Petersburg, Florida 33701, USA, [2]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, J.J. Pickle Research Campus, Building 196, 10100 Burnet Road R2200, Austin, Texas 78758, USA, [3]Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, 1 University Station C1100, Austin, Texas 78712, USA, [4]High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan. †Present address: Department of Geography and Anthropology, Louisiana State University, 227 Howe-Russell Geoscience Complex, Baton Rouge, Louisiana 70803, USA. *e-mail: kdelong@lsu.edu; river@ntu.edu.tw.

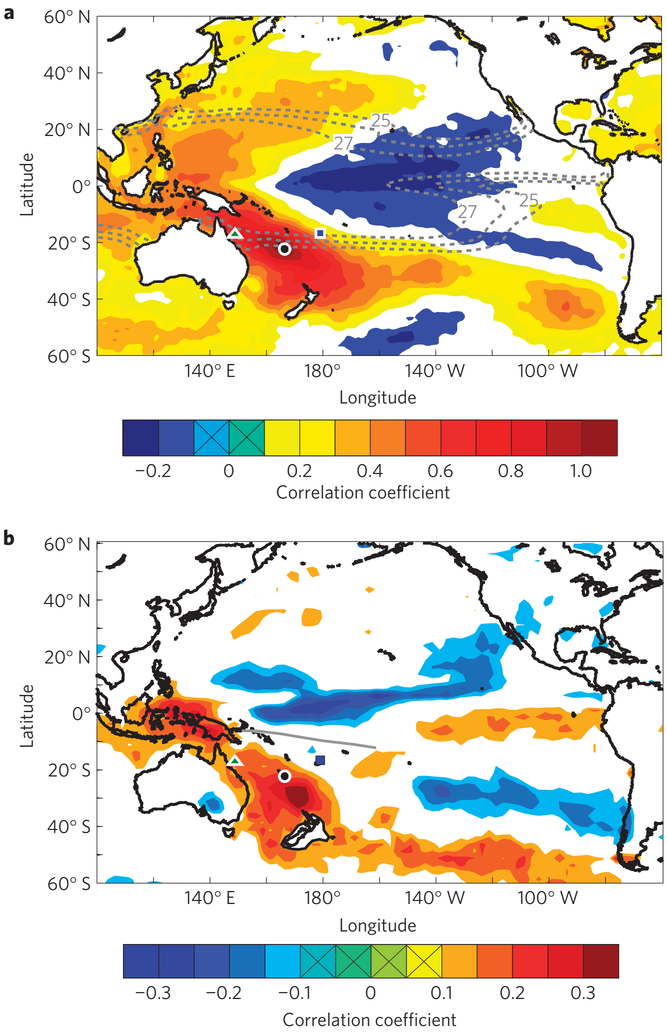

Figure 1 | Correspondence between monthly SSTA in New Caledonia with SSTA and precipitation. Correlations determined for the 1° grid centred on New Caledonia (22.5° S, 166.5° E; filled circle) extracted from a SST database[12] with **a**, monthly SSTA from the same database and **b**, monthly precipitation rate[29] for the interval from 1981 to 2009. Grey lines in **a** denote annual average[12] SST and in **b** the axis of average precipitation associated with the SPCZ. Correlations shown are significant ($r > 0.15$ or < -0.15, $p = 0.05$ and d.f. = 210). Symbols denote locations of reconstructions from Flinders Reef (17.5° S, 148.3° E; filled triangle)[22] and Fiji (16.82° S, 179.2° E; filled square)[16].

Change report[1]. See Methods for details on reconstruction and statistical treatment.

We carried out correlation analysis with databases, which include satellite-derived estimates of SST and precipitation for spatial completeness, to reveal teleconnection patterns for our study site (Fig. 1). The SSTA map reveals a spatial pattern similar to the PDO, IPO (refs 7,9) and El Niño–Southern Oscillation (ENSO; Supplementary Fig. S2) with two exceptions. First, the pattern is shifted westwards with no significant correlation in the easternmost equatorial Pacific where the large ENSO anomalies occur, and second, no significant correlation in the Aleutian Low region, where large anomalies associated with the PDO occur. The correlation map of precipitation with New Caledonia SSTA reveals positive correlation in the maritime continent region, eastern equatorial Pacific and southwest Pacific south of the South Pacific convergence zone (SPCZ); and negative correlation in the South Pacific Gyre region and the northern tropical Pacific. These precipitation patterns suggest teleconnections through Walker and Hadley circulations, similar to the SPDO (ref. 6). Further correlation analysis of our reconstructed SSTA with longer SST and land-based precipitation databases reveals similar spatial patterns, suggesting that these patterns are robust on longer timescales (Supplementary Figs S3–S5). The correlation maps with longer SSTA records (Supplementary Fig. S4) reveal that the reconstructed SSTA captures additional significant negative correlation with SSTA in the eastern tropical Pacific not present in the maps with instrumental SSTA, which may be a result of interpolation reducing variability in these SST databases[15]. The correlation maps of SSTA with longer precipitation records reveal stronger covariance between New Caledonia SSTA and eastern Australia precipitation on interannual timescales (Supplementary Fig. S5).

Cooling in the Northern Hemisphere during the Little Ice Age (LIA) (∼1400–1870) has been linked to decreases in solar irradiance related to sunspot cycles[1]. This cooling may not be globally uniform[20] and climate model experiments reveal regional differences in the temperature response to long-term variations in solar forcing[21]. Our reconstruction reveals ∼0.8 °C centennial scale trends with ∼1.4 °C decadal fluctuations and ∼2.8 °C interannual variability (Fig. 2). Averages are reported with ± one standard deviation (s.d.) with significance of secular trends and averages assessed by Monte Carlo simulation (σ_{MC}; see Methods). We find a progression of warmer–colder–warmer conditions including a warming trend into the twentieth century (+0.73 °C for 1890–1999; $\sigma_{MC} = \pm 0.001\,°C\,yr^{-1}$), which is similar to the global surface temperature trend[1]. The cold period in the early nineteenth century corresponds to a period of increased volcanic activity and to the Dalton sunspot minimum[1] (1795–1830) and the average temperature for our reconstruction (−0.54 ± 0.55 °C, 1 s.d.; $\sigma_{MC} = \pm 0.07\,°C$) is within the range reported for Northern Hemisphere reconstructions (−0.29 to −0.72 °C; ref. 1) for this interval. However, this reconstruction does not reveal lower average temperatures (+0.03 ± 0.60 °C, 1 s.d.; $\sigma_{MC} = \pm 0.05\,°C$) during the Maunder sunspot minimum (1645–1715) whereas Northern Hemisphere reconstructions report colder temperatures for this minimum (−0.32 to −0.73 °C; ref. 1). For the interval from 1649 to 1697, we find even warmer average temperature (+0.18 ± 0.51 °C, 1 s.d.; $\sigma_{MC} = \pm 0.06\,°C$). A comparison of our results with those extracted from a global proxy network study for this site[20] reveal similar warming for the interval from 1649 to 1697; however, results from the proxy network also reveal warmer temperatures in the 1800s. Finally, frequency analysis of our reconstruction reveals a lack of spectral power at 11 years, the periodicity of the sunspot cycle (Fig. 3), suggesting a reduced response to sunspot-related solar variability for our study site.

Previous coral Sr/Ca-based reconstructions from the southwest tropical Pacific allow us to carry out a regional assessment of secular SST variability during the LIA (Supplementary Fig. S6). Comparison between reconstructions from New Caledonia and Flinders Reef[22], offshore of Australia, reveals shared secular variability for the interval from 1705 to 1990 (Pearson's correlation coefficient (r) = 0.30, degrees of freedom (d.f.) = 57 and $p = 0.03$, determined using five-year averages for New Caledonia to match the sampling interval for Flinders Reef). Similar secular variability exists between reconstructions from New Caledonia and Fiji[16] for the interval from 1781 to 1996 ($r = 0.49$, d.f. = 111 and $p = 0.001$ for annual averages). A comparison of these three reconstructions reveals that Fiji has a lower average temperature departure for the interval from 1780 to 1860 (−0.71 ± 0.34 °C, 1 s.d., for Fiji[16]; −0.52 ± 0.24 °C, 1 s.d., for Flinders Reef[22]; and −0.52 ± 0.24 °C, 1 s.d., for New Caledonia, with respect to five-year averages). We cannot assess the presence of warming in Fiji before 1781 owing to the length of that reconstruction.

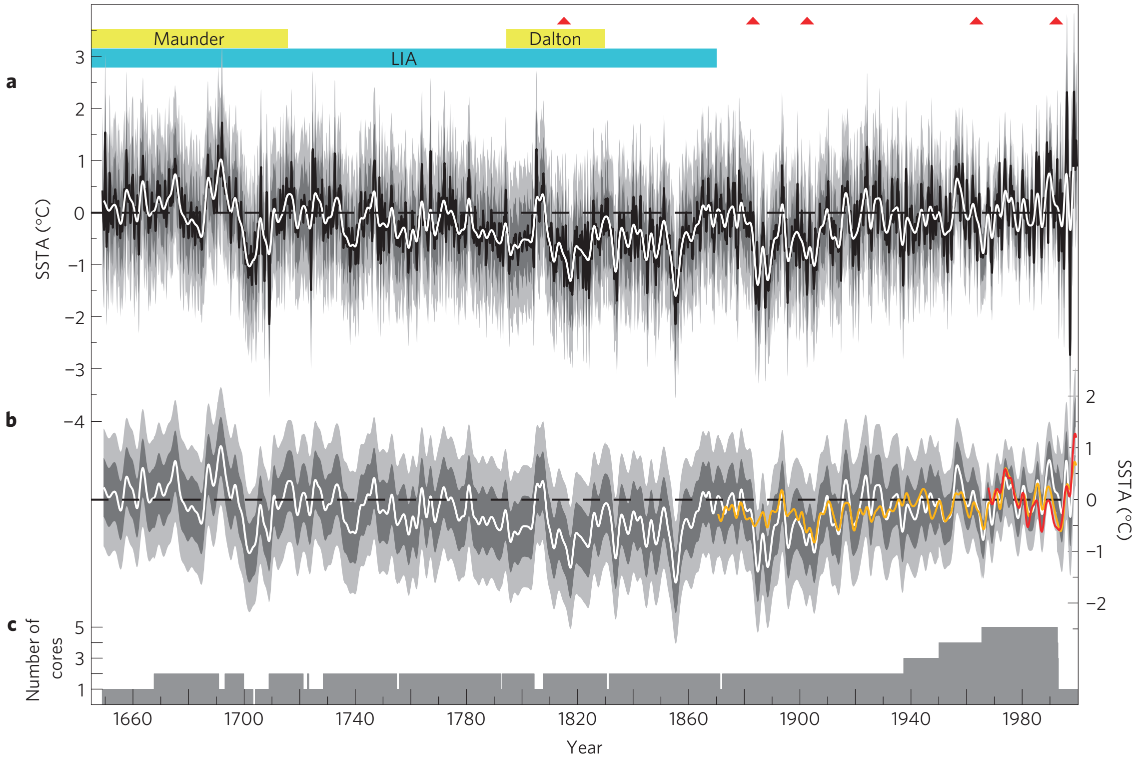

Figure 2 | Temperature reconstruction from coral Sr/Ca variations. a, Monthly SSTA smoothed with a seven-month (black) and 36-month (white) LPFIR filter (90% pass = 11, 62.5 months; respectively). **b**, 36-month smoothed SSTA from **a** shown with similarly smoothed IRD-SST (REF. 15; red) and HadISST-AI (REF. 11; yellow) records. Regression errors (1 s.d., dark grey; 2 s.d., light grey; Supplementary Table S1) are based on **c**, the number of cores. Eruptions[30] with volcanic explosively index ≥ *five* appear along the upper time axis (filled triangle). Yellow and blue bars denote the sunspot minima and LIA, respectively.

Table 1 | Values of *r* between coral cores and SST* .

	92-PAA1 and 92-PAA2[†]	Coral SST[‡] and IRD-SST[§]	Coral SST[‡] and HadISST-AI[‖]
Monthly	0.94	0.94	0.95
Monthly anomaly[¶]	0.51	0.66	0.57
Seven-month[#]	0.56	0.72	0.64
36-month[#]	0.66	0.56	0.72

*All correlations are significant ($p = 0.05$) with d.f. determined with the runs test. [†]The interval is from 1667 to 1992 ($n = 3{,}582$ and d.f. = 981). [‡]Coral SST is based on the multicore coral Sr/Ca-based reconstruction[15,18,19]. [§]IRD-SST is for the interval from 1967 to 1999 (ref. 15; $n = 392$ and d.f. = 106). [‖]HadISST-AI is regional SST (ref. 11) for the interval from 1900 to 1999 (ref. 15; $n = 1{,}198$ and d.f. = 307). [¶]Monthly anomalies are calculated with respect to the interval from 1961 to 1990. [#]Monthly anomalies are smoothed with a low-pass finite impulse response (LPFIR) filter (90% pass = 11 months for seven-month and 62.5 months for 36-month).

These reconstructions provide additional evidence that SST in the southwest tropical Pacific does not vary with long-term variations in solar forcing, similar to the regional differences found in the simulation study[21]. These concurrent centennial scale variations in average SST, along an east and west transect in the southwest Pacific (Fig. 1), suggest oceanic processes are involved in the north–south shift of surface ocean waters in this region. However, further studies are needed to understand the regional dynamics on these timescales.

We assessed our SST reconstruction using frequency analysis methods to determine statistically significant periodicities of variability, separate from the secular trend (Fig. 3). The multitaper method (MTM) spectrum[23] reveals several significant periodicities, which we determined the percentage of variance for each periodicity band. The wavelet spectrum[24] reveals the time intervals and periodicities with significant concentrations of spectral power. The significant decadal periodicities at 14–19 years per cycle (9.5% of variance) modulate in spectral power with time and the significant quasi-bidecadal periodicities at 25–34 years per cycle (8.1% of variance) are present from 1670 to 1893 with a reduction in the width of the periodicity band in the late 1700s. The significant multidecadal periodicities spanning 37–62 years per cycle (4.9% of variance) vary with strength from 1675 to 1745 and 1837 to 1965; however, intervals of these periodicities are under the cone of influence, thus are interpreted with caution. We note that some significant concentrations of power in the interannual (4.8% of variance) to decadal periodicities are centred on large cold anomalies in the reconstruction (1816, 1855, 1883 and 1963), some of which coincide with large volcanic eruptions including Tambora (1815) and Krakatau (1883). These large anomalies produce significant periodicities in the MTM and wavelet spectra that are not related to oscillations.

Our SSTA reconstruction captures similar spatial patterns to those of the SHPDO (ref. 5) and SPDO (ref. 6; Fig. 1 and Supplementary Figs S3 and S4). A comparison of our reconstructed SSTA time series with the SHPDO (ref. 5) and SPDO (ref. 6;

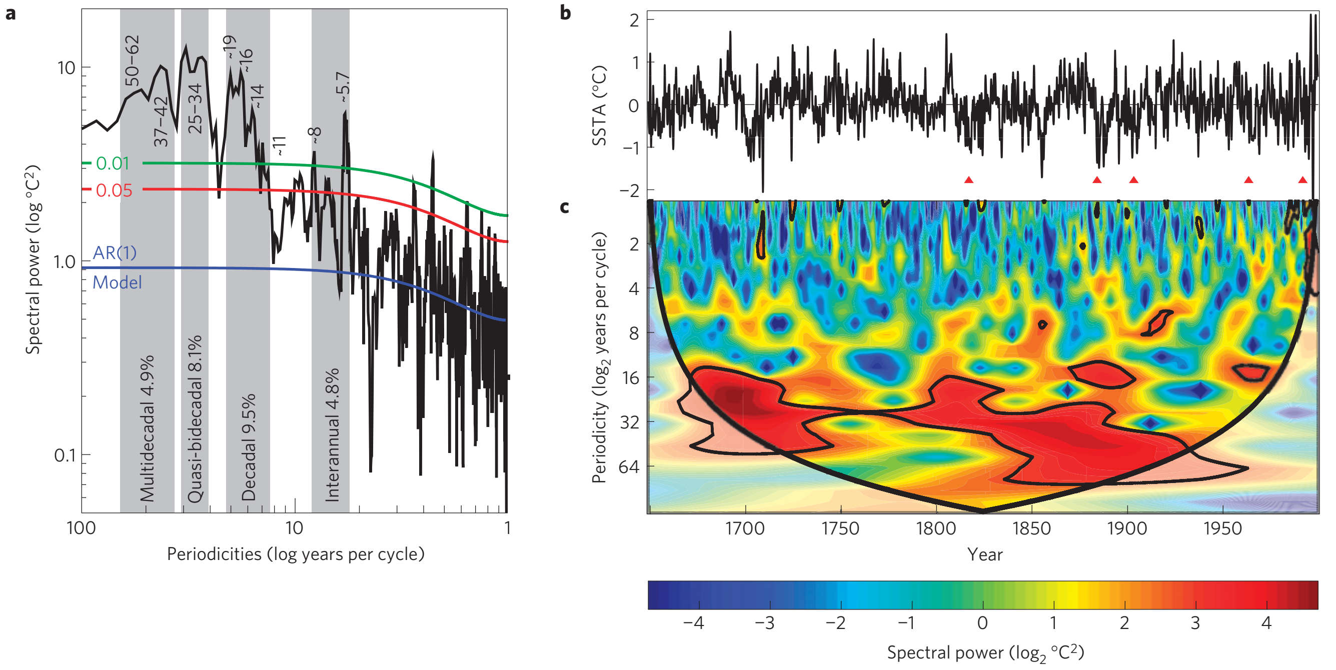

Figure 3 | Results of spectral analysis. a, MTM spectrum (tapers = 3 and resolution = 2; ref. 23) of the **b**, SSTA time series with the secular trend removed (trend = 2.413×10^{-5} yr^2 − 0.088 yr − 0.025). Grey bands denote percentage of variance in significant periodicity bands. **c**, Wavelet spectrum (Morlet mother wavelet)[24] of **b** with thin black contour lines enclosing time-periodicity regions with significant concentrations of spectral power. Heavy black line and shaded area is the cone of influence[24]. Significance ($p = 0.05$) in **a** and **c** tested assuming a first-order autoregressive (AR(1)) model. Volcanic eruptions noted (filled triangle) same as Fig. 2.

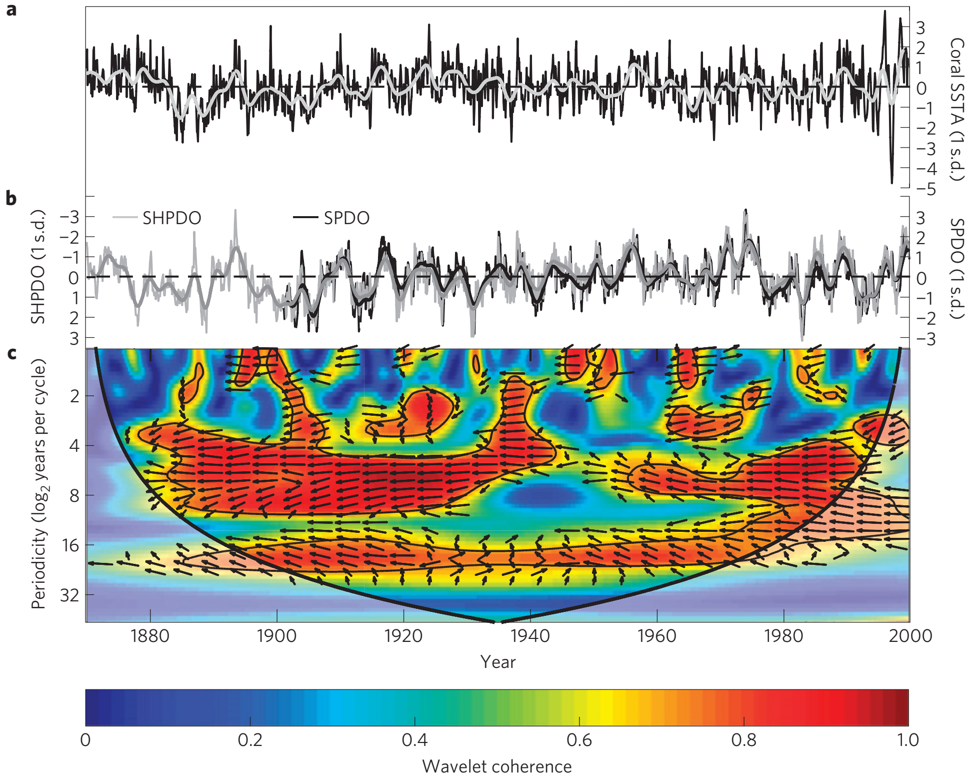

Figure 4 | Decadal scale variability in the southwest Pacific. a, Coral SSTA (secular trend removed, same as Fig. 3b) compared with **b**, the SHPDO (ref. 5) and SPDO (ref. 6). SSTA (thin lines) are calculated with respect to the interval from 1870 to 2000 (similar to the SHPDO; ref. 5), standardized and smoothed with a 36-month LPFIR filter (90% pass = 62.5 months; thick lines). **c**, Cross-wavelet coherence[24,25] of coral SSTA with SHPDO (similar to Fig. 3c) with thin black contour lines enclosing time-periodicity regions with significant concentrations of coherence (r^2) assessed by σ_{MC} ($p = 0.05$; ref. 25). Left arrows indicate negative coherence.

Fig. 4) reveals significant correlation for the interval from 1901 to 1999 ($r = -0.38$, 0.37, d.f. = 257, 273 and $p = 0.0001$ for monthly SHPDO and SPDO, respectively). Cross-wavelet analysis[25] reveals our reconstructed SSTA covaries with the SHPDO in the interannual and decadal periodicities for the interval from 1880 to 1999. Our SSTA reconstruction captured 38% of the variance in the SHPDO on timescales greater than three years ($r = -0.62$, d.f. = 76 and $p = 0.0001$ for 36-month smoothed). Lower correlation with monthly anomalies is due to subannual dating uncertainties as previously discussed[18]. Conversely, the decadal scale variability in our reconstruction does not covary with the PDO (ref. 7) or IPO (ref. 9), which is expected because instrumental records from New Caledonia do not covary with these oscillations (Supplementary Fig. S7).

Our reconstruction is a proxy record of the SHPDO–SPDO, which we extend back to 1649, preceding the anthropogenic-warming trend (before ~1900). The wavelet spectrum (Fig. 3c) reveals the concentrations of significant spectral power decreases in the bidecadal and multidecadal periodicities after 1893 with the only significant concentrations of power occurring in the decadal and interannual periodicities. These decadal periodicities are coherent with the SHPDO and SPDO (Fig. 4). Furthermore, a study of precipitation records from Taiwan and the western Pacific region identified decadal scale variations associated with the SPDO and southwest Pacific SSTA through anomalous flow in the Hadley circulation[6]. Our correlation analysis with both reconstructed and instrumental records reveals similar patterns (Fig. 1 and Supplementary Figs S3–S5), thus supporting the previous study's findings[6]. This 350-year-long reconstruction provides evidence that decadal scale SST variations modulate in periodicity suggesting a temporal shift natural decadal variability for this location, which coincides with the beginning of the anthropogenic-warming trend. These results have implications for understanding what is natural PDV and by extension the natural variability in precipitation for the region south and west of the SPCZ.

Unlike our comparison of the secular variations in reconstructions from the southwest Pacific, the decadal scale variations between New Caledonia and Fiji[16] share some coherence for the interval from 1954 to 1996 ($r = 0.60$, $n = 43$ and $p = 0.001$) with little coherence before 1954 (Supplementary Fig. S8). The lack of coherence may be the result of increasing chronology uncertainty with time or larger non-environmental variability in the reconstruction based on a single core[18] (Supplementary Table S1), or it is possible that real differences exist in decadal variability between these sites, as shown in the instrumental records (Supplementary Fig. S7). We recognize that coral-based reconstructions have limitations. Furthermore, PDO reconstructions do not agree before the twentieth century[17], suggesting that deficiencies in the reconstructions and/or the temporal and spatial patterns of PDV have varied with time[26]. Resolving these differences in decadal scale variability before the twentieth century requires high quality palaeoclimate reconstructions, which this study demonstrates with an improvement to coral-based reconstructions by including an additional core to reduce non-climatic variability and chronology error.

Methods

Cores sampled include: two long cores (92-PAA1 and 92-PAA2) and one shorter core (99-PAA) from a single massive *Porites lutea* colony, and two cores (92-PAC and 92-PAD) from nearby colonies of the same species, all recovered from colonies offshore of Amédée Island, New Caledonia (22° 28.8′ S, 166° 27.9′ E; refs 15,18,19). Previous studies with this suite of coral colonies discuss the location and sampling methods[14,15,19,27]. Examination of scanning electron microscope images and thin sections found no evidence of secondary minerals[15,18]. Elemental ratio (Sr/Ca) determinations follow the method previously described[15]. One-sigma analytical precision of a laboratory internal gravimetric standard is ± 0.010 mmol mol^{-1} ($n = 2{,}445$) and of a homogenized powder from a *P. lutea* coral is ± 0.018 mmol mol^{-1} ($n = 3{,}343$), which is an additional estimate of precision. Samples for ^{230}Th dating[28] were extracted from 92-PAA1 (ref. 18). We established our master chronology with sclerochronology methods[15] confirmed with 11 high-precision ^{230}Th dates[18,28].

Examination of coral Sr/Ca reproducibility (92-PAA1 and 92-PAA2) reveals no significant shifts or differences in the means, standard deviations and annual cycles on any timescale (Supplementary Figs S9, S10 and Table S2). The standard absolute differences between these cores are within 2 s.d. of the magnitude of analytical precision (mean = 0.013 ± 0.009 mmol mol^{-1}, 1 s.d.; Supplementary Fig. S10). Covariance assessment of these cores reveals significant correlation on interannual timescales (Table 1) and these time series are coherent in the frequency domain (interannual–centennial periodicities).

Coral Sr/Ca variations were compiled into a single time series by averaging contemporaneous monthly coral Sr/Ca variations from sampling paths within each colony and then averaging the coral Sr/Ca variations from the colonies together (Supplementary Fig. S9). The monthly resolved coral Sr/Ca variations were converted to SST with the transfer equation previously determined for these corals, which were calibrated to 32 years of *in situ* SST (IRD-SST) from Institut de Recherche pour le Développement - Etudes Climatiques de l'Océan Pacifique tropical (IRD-ECOP) from Amédée Island, New Caledonia[15]. This calibration was verified with the 1° grid centre on our study site (22.5° S, 166.5° E) extracted from the HadISST1.1 database[11] (HadISST-AI), which was adjusted to match the mean and variance of IRD-SST (ref. 15). Strong agreement of the coral Sr/Ca variations with SST in the instrumental period[15,19] (Fig. 2 and Table 1) and reproducibility of the monthly coral Sr/Ca anomalies for more than three centuries[18] (Table 1 and Supplementary Fig. S10) provides evidence for the robustness of our coral Sr/Ca proxy thermometer.

The error of the reconstruction was evaluated for varying scales from a single core to five cores by determining the standard error of regression (σ_R) for the calibration interval (1967–1992; Supplementary Table S1). This allows the σ_R shown by error bars in Fig. 2 to vary with time based on the number of cores. We evaluated the statistical significance of computed values by σ_{MC} with 10,000 realizations of a temperature reconstruction. We allowed the monthly values to vary within the σ_R value determined for each month based on the number of cores, assuming a Gaussian distribution (the residuals have a Gaussian probability distribution function). This method allows us to include non-climatic variability, assessed for intra- and intercolony cores, in our error estimation. We assessed significance of correlations using d.f. determined with the runs test.

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Author contributions

K.L.D. completed sample analysis, data analysis and served as primary author. T.M.Q. supervised K.L.D. in sample analysis, data analysis and writing. F.W.T. recovered the coral cores. K.L. carried out ^{230}Th dating supervised by C-C.S., who was involved in writing of the paper.

Additional information

The authors declare no competing financial interests. Data is archived at the World Data Center for Paleoclimatology, 325 Broadway, Boulder, Colorado; IGBP PAGES/World Data Center for Paleoclimatology, http://www.ncdc.noaa.gov/paleo/corals.html. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.L.D. or C-C.S.