



RESEARCH LETTER

10.1002/2018GL077619

Key Points:

- Coral Sr/Ca reconstructions indicate interannual to centennial-scale SST variations in the tropical western Pacific over the past 1,250 years
- Western tropical Pacific SST was relatively cool during the “Little Ice Age” and warm during the “Medieval Climate Anomaly”
- The late 20th century is the warmest interval of the last millennium in the western tropical Pacific Ocean

Supporting Information:

- Supporting Information S1
- Data Set S1

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Citation:



Chen, T., Cobb, K. M., Roff, G., Zhao, J., Yang, H., Hu, M., & Zhao, K. (2018). Coral-derived western Pacific tropical sea surface temperatures during the last millennium. *Geophysical Research Letters*, 45. <https://doi.org/10.1002/2018GL077619>

Received 20 NOV 2017

Accepted 21 MAR 2018

Accepted article online 26 MAR 2018

Coral-Derived Western Pacific Tropical Sea Surface Temperatures During the Last Millennium

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Abstract Reconstructions of ocean temperatures prior to the industrial era serve to constrain natural climate variability on decadal to centennial timescales, yet relatively few such observations are available from the west Pacific Warm Pool. Here we present multiple coral-based sea surface temperature reconstructions from Yongle Atoll, in the South China Sea over the last ~1,250 years (762–2013 Common Era [CE]). Reconstructed coral Sr/Ca-sea surface temperatures indicate that the “Little Ice Age (1711–1817 CE)” period was ~0.7°C cooler than the “Medieval Climate Anomaly (913–1132 CE)” and that late 20th century warming of the western Pacific is likely unprecedented over the past millennium. Our findings suggest that the Western Pacific Warm Pool may have expanded (contracted) during the Medieval Climate Anomaly (Little Ice Age), leading to a strengthening (weakening) of the Asian summer monsoon, as recorded in Chinese stalagmites.

Plain Language Summary Tropical Pacific climate variability influences global climate system on interannual and longer timescales. In contrast to the eastern and central tropical Pacific, where paleo-sea surface temperature data are relatively abundant, such data are fairly sparse in the western tropical Pacific, which limits our understanding of Pacific Warm Pool and its role in low-frequency climate variability. Here we present a multiple coral-based estimates of monthly resolved sea surface temperature from the Yongle Atoll, South China Sea, that span segments of the last 1,250 years. We demonstrate significant variations in mean sea surface temperature over this period—with warmer conditions during the so-called “Medieval Climate Anomaly” and cooler conditions during the so-called “Little Ice Age,” in keeping with compilations of Northern Hemisphere temperature over this period. Our data also reveal unprecedented warming of sea surface temperatures in the late 20th century and early 21st century that are unprecedented in the past 1,250 years. We believe that our manuscript will be of broad interest to geologists, climatologists, and coral reef scientists, given the paucity of climate records from the region.

1. Introduction

Proxy reconstructions and model simulations of climate variability over the last millennium have aimed to distinguish natural climate variability from anthropogenic climate signals on interannual, decadal, to centennial timescales (Jones & Mann, 2004, and references therein; Mann et al., 2009). Three notable climate epochs, the Medieval Climate Anomaly (MCA, roughly 900–1200 Common Era [CE]), the Little Ice Age (LIA, roughly 1500–1800 CE), and 20th century warming describe the main features of Northern Hemisphere temperatures over the last millennium (Mann et al., 1999; Mann & Jones, 2003; Osborn & Briffa, 2006). Hemispheric-scale warming during the MCA and cooling during the LIA are linked to change in solar and volcanic forcing (e.g., Mann et al., 1999, 2009; PAGES 2k Consortium, 2015), while recent warming reflects the response to anthropogenic greenhouse gas emissions (Intergovernmental Panel on Climate Change Fifth Assessment Report, 2014). However, the global extent and magnitude of the MCA and LIA periods remain unclear, especially across the tropical oceans (McGregor et al., 2015; PAGES 2k Consortium, 2015).

Tropical Pacific climate variability influences global climate on interannual and longer timescales (Alexander et al., 2002; Cobb et al., 2001; Hendy et al., 2002). Therefore, determining the historical natural variability of tropical Pacific climate and controls is of particular importance for predicting future changes in response

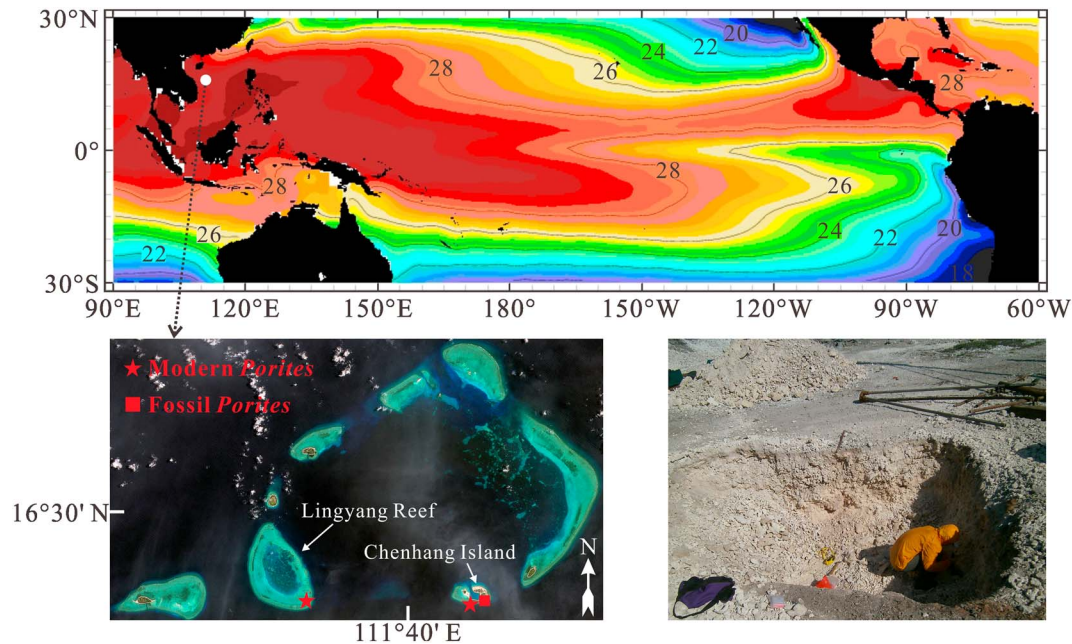


Figure 1. Maps of the study sites. (top) The picture shows the location of sampling sites with monthly (June) climatological SST ($^{\circ}\text{C}$) based on Reynolds and Smith Optimum Interpolation Sea Surface Temperature version 2 data (Reynolds et al., 2002) using the 1971–2000 base period. Yongle Atoll is at the northern edge of the Western Pacific Warm Pool in summer. (bottom) The left picture shows the *Porites* rubble collection sites at the Yongle Atoll and the right picture shows the fieldworks of fossil sample collection on the Chenhang Island.

to continued greenhouse forcing. Debates on the sea surface temperature (SST) variability and corresponding climatic mean state in the tropical Pacific over the last millennium are ongoing. Evidence from coral cores (Cobb et al., 2003), sediment cores (Salvatteci et al., 2014), multiproxy reconstructions (Mann et al., 2009), and climate modeling (Goodwin et al., 2014) suggest the tropical Pacific experienced a cool and possibly dry “La Niña-like” mean state during the MCA interval and a more “El Niño-like” condition in the LIA. Further support for this hypothesis comes from evidence of widespread droughts in the western America during the Mediaeval period, which are suggested to be linked to an anomalously cold tropical Pacific (Booth et al., 2006; Graham et al., 2007; Herweijer et al., 2006; MacDonald, 2007). However, signals from lake sediments in the eastern Pacific indicate a warm period that is more closely related to El Niño-dominated conditions during the MCA period (Fletcher & Moreno, 2012; Ledru et al., 2013; Yan et al., 2011). Furthermore, speleothem records from Indonesia clearly show an El Niño-dominated MCA, related to a weakening of the Pacific Walker circulation and a dry condition (Griffiths et al., 2016).

The tropical western Pacific, especially the Western Pacific Warm Pool (WPWP), is subject to large SST variations on interannual timescales in conjunction with the El Niño-Southern Oscillation (Delcroix & McPhaden, 2002; Picaut et al., 1996; Wang et al., 1999). Western Pacific tropical SSTs are closely related to the East Asian monsoon system, which has a notable impact on the climate variability in East Asia. While high-resolution proxy records of climate variability have been reconstructed from the tropical eastern and central Pacific (e.g., Carré et al., 2014; Cobb et al., 2003; Conroy et al., 2009), climatic reconstructions from the western Pacific are sparse. In complementing speleothems, tree rings, ice cores, and historical documents that are commonly used in paleoclimate composites from temperate regions, SST proxies (e.g., Sr/Ca and $\delta^{18}\text{O}$) in long-lived corals, and bivalves have proven useful in reconstructing interannual to decadal-scale climate variabilities in the tropical Pacific (Cobb et al., 2013; McGregor et al., 2013; Nurhati et al., 2011; Tierney et al., 2015). Individual coral (or bivalve) records are typically decades long, and reconstructing millennial-scale variations from such records often requires large numbers of samples and associated radiometric dates. Coral and bivalve reconstructions are often based on a small number of samples (Deng et al., 2017; Yan et al., 2014, 2015), which likely underestimate the full range of climate variability during a given period. Here we present multiple coral-based SST reconstructions from the Yongle Atoll, western Pacific (Figure 1), that date from 762 to 2013 CE, as determined by high-precision U-Th dating.

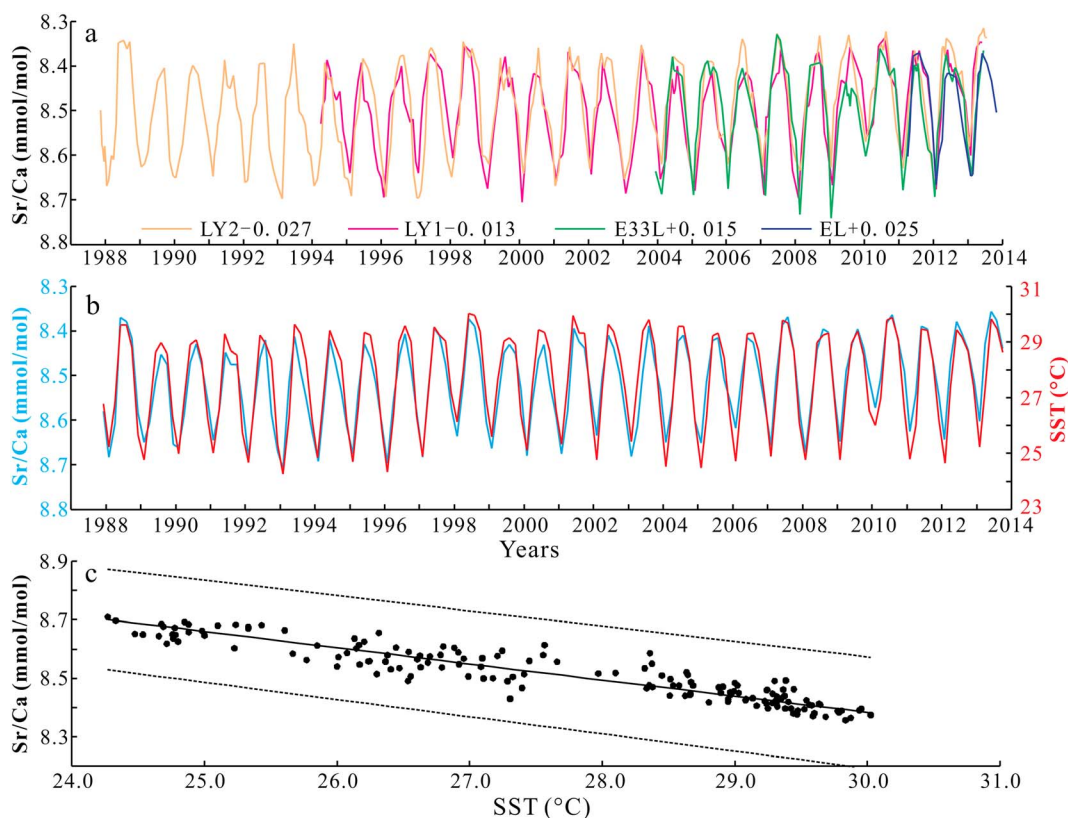


Figure 2. Sr/Ca records of the modern corals. (a) Plot of the original coral Sr/Ca records after applying offsets to match the mean Sr/Ca values in overlapping intervals. (b) Comparison of the stacked coral Sr/Ca record and instrumental bimonthly Extended Reconstructed Sea Surface Temperature version 4 data. Results suggest that Sr/Ca variability here is strongly a function of sea surface temperature (SST). (c) Regression between the stacked coral Sr/Ca record and Extended Reconstructed Sea Surface Temperature version 4 time series. The dashed lines indicate 95% confidence interval. Strong correlation ($R^2 = 0.86$, $n = 156$) between the coral Sr/Ca and instrumental SST records confirms the fidelity of the Sr/Ca-derived SST proxy at this site. The equation is $\text{Sr/Ca} = -0.0556(\pm 0.0016) \times \text{SST} + 10.052(\pm 0.046)$. This slope is very close to the mean value ($-0.06 \text{ mmol/mol } ^\circ\text{C}^{-1}$) of Pacific *Porites* suggested by Corrège (2006).

2. Materials and Methods

Fieldwork was conducted at Yongle Atoll (Figure 1). We recovered cores from four modern *Porites* coral colonies and dozens of approximately 7- to 20-year-long fossil *Porites* rubble at Lingyang Reef and Chenhang Island (Figure 1). Based on diagenetic investigations (X-ray diffraction and scanning electron microscopy; supporting information) and U-Th ages (Table S2), we selected 19 fossil coral samples ranging from 762 to 1817 CE for millimeter-scale Sr/Ca analyses measured by ICP-OES (see the “supporting information” for the further details). Precision for the coral Sr/Ca analyses was 0.014 mmol/mol (1σ), as determined by analyses of repeat standards. The age model for the modern corals was established on the basis of comparing the pronounced seasonal cycles in the Sr/Ca records with corresponding peaks and troughs in SST. Reconstructions of paleo-SST from fossil corals were based upon the calibration between four individual modern *Porites* coral Sr/Ca records and instrumental SST across the 1987 to 2013 interval (Figure 2 and the supporting information).

3. Results

Both modern and fossil corals exhibit clear seasonal cycles in Sr/Ca profiles (Figures 2a and S3). Geochemical proxies in *Porites* corals seem sensitive to growth rate-related “vital effects” (Cohen et al., 2001; de Villiers et al., 1995), which could cause uncertain biases in paleo-SST reconstructions with single *Porites*. To calculate the “intercolony” offsets associated with vital effects in the modern *Porites* Sr/Ca, each individual Sr/Ca time series was centered by removing the mean value in the overlapping interval (2011–2013). The absolute value of the offsets range from 0.013 to 0.027 mmol/mol (Figure 2), yielding relative uncertainties ± 0.22 – 0.45°C

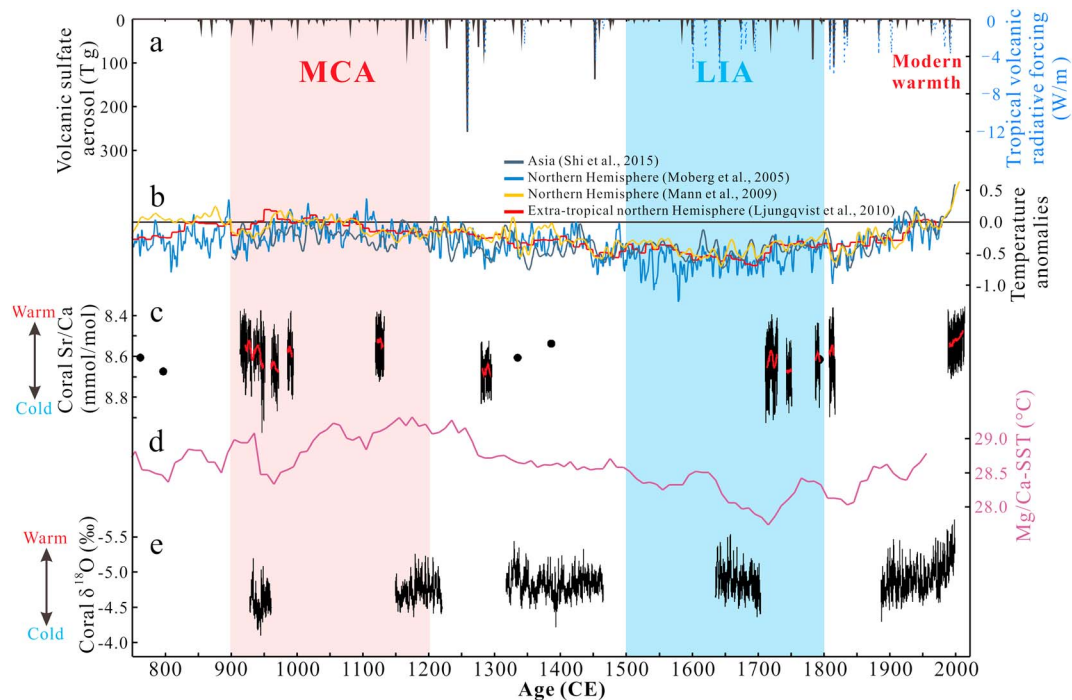


Figure 3. Comparison of coral-based records and other paleo-sequences of tropical Pacific and Northern Hemisphere climate during the last millennium. (a) Global stratospheric volcanic sulfate aerosol injection (Gao et al., 2008) and tropical volcanic radiative forcing (Mann et al., 2005). (b) Multiproxy reconstructed Northern Hemisphere and Asia temperature anomalies. (c) Fossil and stacked modern coral Sr/Ca records in this study. The red lines illustrate the five-year running mean data. Raw Sr/Ca data from fossil corals are shown in Figure S3. The points represent mean Sr/Ca values from the “low-resolution” samples (see the supporting information). The overview of coral records is shown in Table S1. (d) Foraminifera Mg/Ca-based sea surface temperatures from the Makassar Strait, Indo-Pacific warm pool (Oppo et al., 2009). (e) Coral $\delta^{18}\text{O}$ records from the Palmyra Island (Cobb et al., 2003).

($\pm 0.33^\circ\text{C}$ on average) according to the general sensitivity of $0.06 \text{ mmol/mol per } 1^\circ\text{C}$ for the tropical Pacific *Porites* (Corrège, 2006). Stacking of multiple records can effectively minimize individual biases referred to vital effects and eventually increase the accuracy of reconstructions. The composite average was then calculated from the four individual Sr/Ca time series from 1987 to 2013 (Figure 2b). The composite modern coral Sr/Ca record was significantly correlated with instrumental SST ($R^2 = 0.86$; Figure 2c), demonstrating that coral Sr/Ca can be used as a reliable proxy of SST variability at our site. Similarly, Sr/Ca records in multiple fossil *Porites* were used in this study to indicate substantial SST variability in the tropical western Pacific over the past 1,250 years (Figure 3c). Average Sr/Ca values from the MCA (8.575 mmol/mol , $\sim 900\text{--}1150 \text{ CE}$) are slightly (analysis of variance, $F = 9.497$, $p < 0.05$) higher than that in the modern (8.515 mmol/mol , $1987\text{--}2013 \text{ CE}$) corals, but significantly (analysis of variance, $F = 37.606$, $p < 0.001$) lower than Sr/Ca values during the LIA (8.614 mmol/mol , $1711\text{--}1817 \text{ CE}$), suggesting that the MCA was a warm period relative to the LIA. The mean SSTs in the MCA and LIA were calculated based on bulk Sr/Ca values in each period and modern Sr/Ca-SST calibration. The uncertainty resulting from the Sr/Ca analyses and the Sr/Ca-SST calibration was estimated by the Monte-Carlo simulations, and the compounded error for reconstructed Sr/Ca-SSTs by adding the intercolony offsets related to vital effects was 0.5°C (1σ ; see supporting information).

4. Discussion

Our coral Sr/Ca records over the last 1,250 years (Figure 3c) are largely consistent with the foraminiferal Mg/Ca-SST records from the Makassar Strait, Indo-Pacific warm pool (Oppo et al., 2009; Figure 3d), and are in broad agreement with long-term trends in surface temperature reconstructions from Asia and the Northern Hemisphere (Figure 3b) during the last millennium. This suggests that the climate in the tropical western Pacific was controlled by hemispherical or global forcing factors (e.g., solar forcing) at centennial to millennial timescales. Our long-term coral Sr/Ca records indicate that SST in the Western Pacific was significantly cooler during the LIA than either modern or MCA periods. The low Sr/Ca values observed in the

modern record indicate that sustained periods of warmer SST in the late 20th/early 21st is unprecedented over the last 1,250 years. Based on the calibration between modern coral Sr/Ca and instrumental Extended Reconstructed Sea Surface Temperature version 4, the reconstructed mean SSTs in the MCA (913–1132 CE) and LIA (1711–1817 CE) are 26.5 and 25.8°C, respectively, which are ~0.7 and ~1.4°C lower than the average annual temperatures derived from the local Extended Reconstructed Sea Surface Temperature version 4 record of the 20th century (27.2°C, 1901–2000 CE; Figure S4). Our finding of warmer SSTs in the 20th/21st centuries and MCA period and cooler SSTs during the LIA is broadly consistent with other records from the western Pacific region. For example, SST during the MCA in the Southern Okinawa Trough (East China Sea) was 25.7°C, 0.4°C lower than that in the 20th century (Wu et al., 2012). Similarly, planktonic foraminiferal Mg/Ca-SST records from the Makassar Strait (Indonesia) showed warm temperatures and high salinities occurred during the MCA, while the SSTs during the LIA were ~1.5°C cooler than present (Newton et al., 2006). At New Caledonia, southwest tropical Pacific, surface temperatures from 1701 to 1761 CE were on average 1.4°C cooler than present (Corrège et al., 2001). Even in the central tropical Pacific, coral Sr/Ca-SST records indicate that temperatures were ~1.7°C cooler during the LIA (1630–1703 CE) compared with the late 20th century (Sayani et al., 2015).

Higher coral $\delta^{18}\text{O}$ values (928–961 CE and 1149–1220 CE; Cobb et al., 2003; Figure 3e) and negative diatom T/E index (~1000–1300 CE; Conroy et al., 2009) indicate that the MCA was a relatively cool and/or dry period, potentially related to a persistent La Niña conditions in the tropical Pacific. The La Niña-like mean state, corresponding with an anomalously strong Pacific zonal SST gradient, was attributed to a combination of relatively high solar irradiance (Emile-Geay et al., 2013; Mann et al., 2009), inactive tropical volcanism (Mann et al., 2009), and enhanced Atlantic meridional overturning circulation (Trouet et al., 2009). The warmer SST in the western Pacific over the MCA (Figures 3c and 3d), combined with the cooler SSTs in the central and eastern Pacific (Cobb et al., 2003; Conroy et al., 2009), is compatible with the La Niña-like mean state related to an enhanced zonal temperature gradient, similar to the La Niña events according to modern instrumental observations (Wang et al., 1999). However, simulations with Community Climate System Model version 4 did not reproduce a cooling in the Niño 3.4 region during the MCA relative to the LIA (Landrum et al., 2013). Similarly, foraminifera Mg/Ca records from the Galápagos sediment cores revealed warm SSTs at the peak of the MCA (~950–1150 CE; Rustic et al., 2015), consistent with evidence for a more frequent El Niño pattern in the eastern equatorial Pacific during the MCA relative to the LIA (Conroy et al., 2008; Moy et al., 2002). In summary, more high-resolution paleodata are needed over the last millennia to resolve these apparent conflicts, particularly in the eastern and central tropical Pacific regions.

Two periods of positive Sr/Ca anomalies, potentially reflecting relatively cool periods of 30–60 years in duration, were evident during the MCA (~950 CE and ~1300 CE). The short-lived cold period around ~950 CE based on our coral Sr/Ca records (~945–972 CE; Figure 3c) associated with anomalously low SST (25.3°C on average) is generally consistent with the central Pacific coral record (Cobb et al., 2003; Figure 3e) and the western Pacific Mg/Ca-SST profile (Oppo et al., 2009; Figure 3d). However, this period is absent from the eastern Pacific records derived from Mg/Ca-SST (Rustic et al., 2015). It is unclear whether this is because the cold period is absent from the eastern Pacific or alternatively whether this reflects low resolution in the eastern Pacific SST reconstructions. Although the origin of this anomaly is unknown, it is unlikely to be associated with volcanic activities, as volcanic forcing was relatively weak around 950 CE (Figure 3a). The second cold period around 1300 CE (~1279–1335 CE; Figure 3c) associated with anomalously low SST (25.5°C on average) is in agreement with the Niño3.4 Community Climate System Model version 4 simulation (Landrum et al., 2013), which simulated a 1.0–1.5°C cooling during this time. Nunn (2007, 2012) defined this period of rapid cooling (~1250–1350 CE) as the “CE 1300 Event” and reported that around 1300 CE, the entire Pacific Basin was affected by comparatively rapid cooling, sea level fall (70–80 cm), and a food crisis for coastal dwellers throughout the tropical Pacific Islands. This cold event is likely associated with a period of large volcanic eruptions during the 13th century (Landrum et al., 2013), including the largest eruption of the last millennium, which occurred in 1259 CE, together with four moderate to large eruptions in 1228 CE, 1268 CE, 1275 CE, and 1285 CE (Gao et al., 2008).

The WPWP's vast moisture and heat exchange strongly influence global climate and play a crucial role as a “switch” in moisture supply for precipitation in East Asia after the onset of the Asian summer monsoon (Ding & Chan, 2005). Our study site Yongle Atoll sits near the north margin of the WPWP (Figure 1), where

SST is sensitive to changes in the temperature, position, and size of WPWP. During the modern warmth, the Warm Pool has extended both latitudinally and longitudinally concurrent with significant surface warming and freshening (Cravatte et al., 2009). During the MCA, our data show that with the exception of the ~950 CE cooling anomaly, the WPWP expanded beyond the Yongle Atoll, indicating a northward expansion of the WPWP. Stalagmite $\delta^{18}\text{O}$ records (Zhang et al., 2008) indicate a strengthened summer monsoon during the MCA, indicating some support for warmer WPWP SSTs driving enhanced monsoonal circulation during this time. Indeed, peat pollen (Ren, 1998) and lake sediments (Ji et al., 2005; Liu et al., 2011) also reflect relatively abundant precipitation in China during the MCA. Foraminiferal evidence for a more northerly position of the Intertropical Convergence Zone during the MCA is also consistent with this framework (Newton et al., 2006). During the LIA, the seasonal Sr/Ca-SST amplitude was relatively larger ($3.0 \pm 1.1^\circ\text{C}$) than during the MCA ($2.5 \pm 1.1^\circ\text{C}$), which is mainly associated with the low winter SSTs (Figure S4). We suggest that cool conditions at our study sites during the LIA are related to a contraction of the WPWP following the MCA, associated with a strengthened winter monsoon (Qiao et al., 2011; Yang et al., 2015) and more southerly position of the Intertropical Convergence Zone (Richey & Sachs, 2016).

5. Conclusions

We present a new coral-based SST reconstruction from the West Pacific Warm Pool spanning multiple centuries over the period from 762 to 2013 CE. Our coral Sr/Ca profile is consistent with the foraminifera Mg/Ca-SST time series in the Makassar Strait (Oppo et al., 2009), and both track Northern Hemisphere temperatures on centennial timescales, consistent with a dominant role for external climate forcings (solar and volcanic variabilities) in driving low-frequency SST variations in this region. Modern coral-based estimates of SST during the late 20th century and early 21st century indicate a period of warm SST that is likely unprecedented in the western Pacific region throughout the last 1,250 years, in line with many other studies that highlight the dominant role of anthropogenic greenhouse forcing in driving recent ocean warming.

Acknowledgments

The authors thank Faye Liu (RIF), Ai Nguyen (RIF), and Yuexing Feng (RIF) for U/Th dating lab assistance. We also thank Ziyun Lin (OMG) for coral sample shipment in the fieldtrip. This study was supported by the National Natural Science Foundation of China (41476038 and 41676049) and the CAS Youth Innovation Promotion Association (2015284). The details of methods and original data in this paper are shown in the supporting information. The original coral Sr/Ca data can be found in the supplemental EXCEL file "Porites Sr_Ca data from Yongle Atoll." The authors have no conflict of interests to declare.

References

- Alexander, M. A., Blade, I., Newman, M., Lanzante, J. R., Lau, N. C., & Scott, J. D. (2002). The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. *Journal of Climate*, *15*(16), 2205–2231. [https://doi.org/10.1175/1520-0442\(2002\)015%3C2205:TABTIO%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015%3C2205:TABTIO%3E2.0.CO;2)
- Bohonak, A. J. (2004). RMA: Software for reduced major axis regression. Retrieved from <http://www.bio.sdsu.edu/pub/andy/RMA.html>
- Booth, R. K., Notaro, M., Jackson, S. T., & Kutzbach, J. E. (2006). Widespread drought episodes in the western Great Lakes region during the past 2000 years: Geographic extent and potential mechanisms. *Earth and Planetary Science Letters*, *242*(3–4), 415–427. <https://doi.org/10.1016/j.epsl.2005.12.028>
- Carré, M., Sachs, J. P., Purca, S., Schauer, A. J., Braconnot, P., Falcón, R. A., et al. (2014). Holocene history of ENSO variance and asymmetry in the eastern tropical Pacific. *Science*, *345*(6200), 1045–1048. <https://doi.org/10.1126/science.1252220>
- Carré, M., Sachs, J. P., Wallace, J. M., & Favier, C. (2012). Exploring errors in paleoclimate proxy reconstructions using Monte Carlo simulations: Paleotemperature from mollusk and coral geochemistry. *Climate of the Past*, *8*(2), 433–450. <https://doi.org/10.5194/cp-8-433-2012>
- Clark, T. R., Roff, G., Zhao, J. X., Feng, Y. X., Done, T. J., & Pandolfi, J. M. (2014). Testing the precision and accuracy of the UeTh chronometer for dating coral mortality events in the last 100 years. *Quaternary Geochronology*, *23*, 35–45. <https://doi.org/10.1016/j.quageo.2014.05.002>
- Clark, T. R., Zhao, J. X., Roff, G., Feng, Y. X., Done, T. J., Nothdurft, L. D., & Pandolfi, J. M. (2014). Discerning the timing and cause of historical mortality events in modern Porites from the Great Barrier Reef. *Geochimica et Cosmochimica Acta*, *138*, 57–80. <https://doi.org/10.1016/j.gca.2014.04.022>
- Cobb, K. M., Charles, C. D., Cheng, H., & Edwards, R. L. (2003). El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, *424*(6946), 271–276. <https://doi.org/10.1038/nature01779>
- Cobb, K. M., Charles, C. D., & Hunter, D. E. (2001). A central tropical Pacific coral demonstrates Pacific, Indian, and Atlantic decadal climate connections. *Geophysical Research Letters*, *28*, 2209–2212. <https://doi.org/10.1029/2001GL012919>
- Cobb, K. M., Westphal, N., Sayani, H. R., Watson, J. T., Di Lorenzo, E., Cheng, H., et al. (2013). Highly variable El Niño-Southern Oscillation throughout the Holocene. *Science*, *339*(6115), 67–70. <https://doi.org/10.1126/science.1228246>
- Cohen, A. L., Layne, G. D., Hart, S. R., & Lobel, P. S. (2001). Kinetic control of skeletal Sr/Ca in a symbiotic coral: Implications for the paleotemperature proxy. *Paleoceanography*, *16*, 20–26. <https://doi.org/10.1029/1999PA000478>
- Conroy, J. L., Overpeck, J. T., Cole, J. E., Shanahan, T. M., & Steinitz-Kannan, M. (2008). Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews*, *27*(11–12), 1166–1180. <https://doi.org/10.1016/j.quascirev.2008.02.015>
- Conroy, J. L., Restrepo, A., Overpeck, J. T., Steinitz-Kannan, M., Cole, J. E., Bush, M. B., & Colinvaux, P. A. (2009). Unprecedented recent warming of surface temperatures in the eastern tropical Pacific Ocean. *Nature Geoscience*, *2*(1), 46–50. <https://doi.org/10.1038/ngeo390>
- Corrège, T. (2006). Sea surface temperature and salinity reconstruction from coral geochemical tracers. *Palaeogeography Palaeoclimatology Palaeoecology*, *232*(2–4), 408–428. <https://doi.org/10.1016/j.palaeo.2005.10.014>
- Corrège, T., Quinn, T., Delcroix, T., Le Cornec, F., Récy, J., & Cabioch, G. (2001). Little Ice Age sea surface temperature variability in the southwest tropical Pacific. *Geophysical Research Letters*, *28*, 3477–3480. <https://doi.org/10.1029/2001GL013216>
- Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M., & Leloup, J. (2009). Observed freshening and warming of the western Pacific Warm Pool. *Climate Dynamics*, *2009*(33), 565–589.

- de Villiers, S., Nelson, B. K., & Chivas, A. R. (1995). Biological controls on coral Sr/Ca and $\delta^{18}\text{O}$ reconstructions of sea surface temperatures. *Science*, 269(5228), 1247–1249. <https://doi.org/10.1126/science.269.5228.1247>
- Delcroix, T., & McPhaden, M. (2002). Interannual sea surface salinity and temperature changes in the western Pacific warm pool during 1992–2000. *Journal of Geophysical Research*, 107(C12), 8002. <https://doi.org/10.1029/2001JC000862>
- Deng, W., Liu, X., Chen, X., Wei, G., Zeng, T., Xie, L., & Zhao, J. (2017). A comparison of the climates of the Medieval Climate Anomaly, Little Ice Age, and Current Warm Period reconstructed using coral records from the northern South China Sea. *Journal of Geophysical Research: Oceans*, 122, 264–275. <https://doi.org/10.1002/2016JC012458>
- Ding, Y., & Chan, J. C. L. (2005). The East Asian summer monsoon: an overview. *Meteorology and Atmospheric Physics*, 89, 117–142.
- Emile-Geay, J., Cobb, K. M., Mann, M. E., & Wittenberg, A. T. (2013). Estimating central equatorial Pacific SST variability over the past Millennium. Part II: Reconstructions and implications. *Journal of Climate*, 26(7), 2329–2352. <https://doi.org/10.1175/JCLI-D-11-00511.1>
- Fletcher, M. S., & Moreno, P. I. (2012). Vegetation, climate and fire regime changes in the Andean region of southern Chile (38°S) covaried with centennial-scale climate anomalies in the tropical Pacific over the last 1500 years. *Quaternary Science Reviews*, 46, 46–56. <https://doi.org/10.1016/j.quascirev.2012.04.016>
- Gao, C., Robock, A., & Ammann, C. (2008). Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. *Journal of Geophysical Research*, 113, D23111. <https://doi.org/10.1029/2008JD010239>
- Goodwin, I. D., Browning, S., Lorrey, A. M., Mayewski, P. A., Phipps, S. J., Bertler, N. A. N., et al. (2014). A reconstruction of extratropical Indo-Pacific sea-level pressure patterns during the Medieval Climate Anomaly. *Climate Dynamics*, 43(5–6), 1197–1219. <https://doi.org/10.1007/s00382-013-1899-1>
- Graham, N. E., Hughes, M. K., Ammann, C. M., Cobb, K. M., Hoerling, M. P., Kennett, D. J., et al. (2007). Tropical Pacific–mid-latitude teleconnections in medieval times. *Climatic Change*, 83(1–2), 241–285. <https://doi.org/10.1007/s10584-007-9239-2>
- Griffiths, M. L., Kimbrough, A. K., Gagan, M., Drysdale, R. N., Cole, J. E., Johnson, K. R., et al. (2016). Western Pacific hydroclimate linked to global climate variability over the past two millennia. *Nature Communications*, 7, 11719. <https://doi.org/10.1038/ncomms11719>
- Hendy, E. J., Gagan, M. K., Alibert, C. A., McCulloch, M. T., Lough, J. M., & Isdale, P. J. (2002). Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science*, 295(5559), 1511–1514. <https://doi.org/10.1126/science.1067693>
- Herweijer, C., Seager, R., & Cook, E. R. (2006). North American droughts of the mid to late nineteenth century: A history, simulation and implication for Mediaeval drought. *The Holocene*, 16(2), 159–171. <https://doi.org/10.1191/0959683606h1917p>
- IPCC (2014). IPCC Fifth Assessment Synthesis Report (AR5) (151 pp.). Geneva, Switzerland: IPCC.
- Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L., & Liu, X. (2005). Asian monsoon oscillations in the northeastern Qinghai–Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters*, 233(1–2), 61–70. <https://doi.org/10.1016/j.epsl.2005.02.025>
- Jones, P. D., & Mann, M. E. (2004). Climate over past Millennia. *Reviews of Geophysics*, 42, RG2002. <https://doi.org/10.1029/2003RG000143>
- Landrum, L., Otto-Bliesner, B. L., Wahl, E. R., Conley, A., Lawrence, P. J., Rosenbloom, N., & Teng, H. (2013). Last millennium climate and its variability in CCSM4. *Journal of Climate*, 26(4), 1085–1111. <https://doi.org/10.1175/JCLI-D-11-00326.1>
- Ledru, M. P., Jomelli, V., Samaniego, P., Vuille, M., Hidalgo, S., Herrera, M., & Ceron, C. (2013). The Medieval Climate Anomaly and the Little Ice Age in the eastern Ecuadorian Andes. *Climate of the Past*, 9(1), 307–321. <https://doi.org/10.5194/cp-9-307-2013>
- Liu, J., Chen, F., Chen, J., Xia, D., Xu, Q., Wang, Z., & Li, Y. (2011). Humid Medieval Warm Period recorded by magnetic characteristics of sediments from Gonghai Lake, Shanxi, North China. *Chinese Science Bulletin*, 56(23), 2464–2474. <https://doi.org/10.1007/s11434-011-4592-y>
- Ljungqvist, F. C. (2010). A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler*, 92A(3), 339–351.
- MacDonald, G. M. (2007). Severe and sustained drought in southern California and the West: Present conditions and insights from the past on causes and impacts. *Quaternary International*, 173–174, 87–100. <https://doi.org/10.1016/j.quaint.2007.03.012>
- Mann, M. E., Bradley, R. S., & Hughes, M. K. (1999). Northern hemisphere temperature during the past Millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters*, 26, 759–762. <https://doi.org/10.1029/1999GL900070>
- Mann, M. E., Cane, M. A., Zebiak, S. E., & Clement, A. (2005). Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate*, 18(3), 447–456. <https://doi.org/10.1175/JCLI-3276.1>
- Mann, M. E., & Jones, P. D. (2003). Global surface temperature over the past two millennia. *Geophysical Research Letters*, 30(15), 1820. <https://doi.org/10.1029/2003GL017814>
- Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., et al. (2009). Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, 326(5957), 1256–1260. <https://doi.org/10.1126/science.1177303>
- McGregor, H. V., Evans, M. N., Goosse, H., Leduc, G., Martrat, B., Addison, J. A., et al. (2015). Robust global ocean cooling trend for the pre-industrial Common Era. *Nature Geoscience*, 8(9), 671–677. <https://doi.org/10.1038/ngeo2510>
- McGregor, H. V., Fischer, M. J., Gagan, M. K., Fink, D., Phipps, S. J., Wong, H., & Woodroffe, C. D. (2013). A weak El Niño/Southern Oscillation with delayed seasonal growth around 4,300 years ago. *Nature Geoscience*, 6(11), 949–953. <https://doi.org/10.1038/ngeo1936>
- Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., & Karlén, W. (2005). Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature*, 433(7026), 613–617. <https://doi.org/10.1038/nature03265>
- Moy, C. M., Seltzer, G. O., Rodbell, D. T., & Anderson, D. M. (2002). Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, 420(6912), 162–165. <https://doi.org/10.1038/nature01194>
- Newton, A., Thunell, R., & Stott, L. (2006). Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters*, 33, L19710. <https://doi.org/10.1029/2006GL027234>
- Nunn, P. D. (2007). The A.D. 1300 event in the Pacific Basin. *The Geographical Review*, 97(1), 1–23.
- Nunn, P. D. (2012). Disruption of coastal societies in the Pacific Islands from rapid sea-level fall about AD 1300: New evidence from northern Viti Levu Island, Fiji. *Journal of Coastal Conservation*, 16(2), 199–209. <https://doi.org/10.1007/s11852-010-0142-z>
- Nurhati, I. S., Cobb, K. M., & Lorenzo, E. D. (2011). Decadal-scale SST and salinity variations in the central tropical Pacific: Signatures of natural and anthropogenic climate change. *Journal of Climate*, 24(13), 3294–3308. <https://doi.org/10.1175/2011JCLI3852.1>
- Oppo, D. W., Rosenthal, Y., & Linsley, B. K. (2009). 2000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature*, 460(7259), 1113–1116. <https://doi.org/10.1038/nature08233>
- Osborn, T. J., & Briffa, K. R. (2006). The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science*, 311(5762), 841–844. <https://doi.org/10.1126/science.1120514>
- PAGES 2k Consortium (2015). Continental-scale temperature variability during the past two millennia. *Nature Geoscience*, 6(5), 339–346. <https://doi.org/10.1038/ngeo1797>

- Pailard, D., Labeyrie, L., & Yiou, P. (1996). Macintosh program performs time-series analysis. *Eos, Transactions American Geophysical Union*, 77(39), 379. <https://doi.org/10.1029/96EO00259>
- Picaut, J., Loualalen, M., Menkes, C., Delcroix, T., & McPhaden, M. J. (1996). Mechanism of the zonal displacements of the Pacific Warm Pool: Implications for ENSO. *Science*, 274(5292), 1486–1489. <https://doi.org/10.1126/science.274.5292.1486>
- Qiao, S., Yang, Z., Liu, J., Sun, X., Xiang, R., Shi, X., et al. (2011). Records of late-Holocene East Asian winter monsoon in the East China Sea: Key grain-size component of quartz versus bulk sediments. *Quaternary International*, 230(1-2), 106–114. <https://doi.org/10.1016/j.quaint.2010.01.020>
- Ren, G. (1998). Pollen evidence for increased summer rainfall in the Medieval warm period at Maili, Northeast China. *Geophysical Research Letters*, 25, 1931–1934. <https://doi.org/10.1029/98GL01508>
- Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., & Wang, W. (2002). An improved in situ and satellite SST analysis for climate. *Journal of Climate*, 15(13), 1609–1625. [https://doi.org/10.1175/1520-0442\(2002\)015%3C1609:AIISAS%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015%3C1609:AIISAS%3E2.0.CO;2)
- Richey, J. N., & Sachs, J. P. (2016). Precipitation changes in the western tropical Pacific over the past millennium. *Geology*, 44(8), 671–674. <https://doi.org/10.1130/G37822.1>
- Roche, R. C., Perry, C. T., Smithers, S. G., Leng, M. J., Grove, C. A., Sloane, H. J., & Unsworth, C. E. (2014). Mid-Holocene sea surface conditions and riverine influence on the inshore Great Barrier Reef. *The Holocene*, 24(8), 885–897. <https://doi.org/10.1177/0959683614534739>
- Rustic, G. T., Koutavas, A., Marchitto, T. M., & Linsley, B. K. (2015). Dynamical excitation of the tropical Pacific Ocean and ENSO variability by Little Ice Age cooling. *Science*, 350(6267), 1537–1541. <https://doi.org/10.1126/science.aac9937>
- Salvattei, R., Gutiérrez, D., Field, D., Sifeddine, A., Ortlieb, L., Bouloubassi, I., et al. (2014). The response of the Peruvian Upwelling Ecosystem to centennial-scale global change during the last two millennia. *Climate of the Past*, 10(2), 715–731. <https://doi.org/10.5194/cp-10-715-2014>
- Sayani, H. R., Cobb, K. M., Cohen, A. L., Elliott, W. C., Nurhati, I. S., Dunbar, R. B., et al. (2011). Effects of diagenesis on paleoclimate reconstructions from modern and young fossil corals. *Geochimica et Cosmochimica Acta*, 75(21), 6361–6373. <https://doi.org/10.1016/j.gca.2011.08.026>
- Sayani, H. R., Cobb, K. M., Khare, A., Stone, C., Grothe, P. R., Chen, T., et al. (2015). Central tropical Pacific SST and salinity variability over the Little Ice Age Abstract PP13D-02 Presented at the 2015 AGU Fall Meeting, San Francisco, CA.
- Schrag, D. P. (1999). Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. *Paleoceanography*, 14, 97–102. <https://doi.org/10.1029/1998PA900025>
- Shi, F., Ge, Q., Yang, B., Li, J., Yang, F., Ljungqvist, F. C., et al. (2015). A multi-proxy reconstructions of spatial and temporal variations in Asian summer temperatures over the last millennium. *Climate Change*, 131(4), 663–676. <https://doi.org/10.1007/s10584-015-1413-3>
- Smithers, S. G., & Woodroffe, C. D. (2001). Coral microatolls and 20th century sea level in the eastern Indian Ocean. *Earth and Planetary Science Letters*, 191(1-2), 173–184. [https://doi.org/10.1016/S0012-821X\(01\)00417-4](https://doi.org/10.1016/S0012-821X(01)00417-4)
- Solow, A. R., & Huppert, A. (2004). A potential bias in coral reconstruction of sea surface temperature. *Geophysical Research Letters*, 31, L06308. <https://doi.org/10.1029/2003GL019349>
- Tierney, J. E., Abram, N. J., Anchukaitis, K. J., Evans, M. N., Giry, C., Kilbourne, K. H., et al. (2015). Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography*, 30, 226–252. <https://doi.org/10.1002/2014PA002717>
- Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., & Frank, D. C. (2009). Persistent positive north Atlantic Oscillation Mode dominated the Medieval Climate Anomaly. *Science*, 324, 78–80.
- Wang, C., Weisberg, R. H., & Virmani, J. I. (1999). Western Pacific Interannual variability associated with the El Niño-Southern Oscillation. *Journal of Geophysical Research*, 104, 5131–5149. <https://doi.org/10.1029/1998JC900090>
- Woodroffe, C. D., Beech, M. R., & Gagan, M. K. (2003). Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls. *Geophysical Research Letters*, 30(7), 1358. <https://doi.org/10.1029/2002GL015868>
- Woodroffe, C. D., & Gagan, M. K. (2000). Coral microatolls from the central Pacific record late Holocene El Niño. *Geophysical Research Letters*, 27, 1511–1514. <https://doi.org/10.1029/2000GL011407>
- Wu, W., Tan, W., Zhou, L., Yang, H., & Xu, Y. (2012). Sea surface temperature variability in southern Okinawa Trough during last 2700 years. *Geophysical Research Letters*, 39, L14705. <https://doi.org/10.1029/2012GL052749>
- Yan, H., Soon, W., & Wang, Y. (2015). A composite sea surface temperature record of the northern South China Sea for the past 2500 years: A unique look into seasonality and seasonal climate changes during warm and cold periods. *Earth Science Reviews*, 141, 122–135. <https://doi.org/10.1016/j.earscirev.2014.12.003>
- Yan, H., Sun, L., Shao, D., Wang, Y., & Wei, G. (2014). Higher sea surface temperature in the northern South China Sea during the natural warm periods of late Holocene than recent decades. *Chinese Science Bulletin*, 59(31), 4115–4122. <https://doi.org/10.1007/s11434-014-0317-3>
- Yan, H., Sun, L., Wang, Y., Huang, W., Qiu, S., & Yang, C. (2011). A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. *Nature Geoscience*, 4(9), 611–614. <https://doi.org/10.1038/ngeo1231>
- Yang, W., Zhou, X., Xiang, R., Wang, Y., Shao, D., & Sun, L. (2015). Reconstruction of winter monsoon strength by elemental ratio of sediments in the East China Sea. *Journal of Asian Earth Sciences*, 114, 467–475. <https://doi.org/10.1016/j.jseaes.2015.04.010>
- Zhang, P., Cheng, H., Edwards, R. L., Chen, F., Wang, Y., Yang, X., et al. (2008). A test of climate, Sun, and culture relationships from an 1810-year Chinese cave record. *Science*, 322(5903), 940–942. <https://doi.org/10.1126/science.1163965>