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Wet and cold climate conditions recorded by coral geochemical proxies during the beginning of the first millennium CE in the northern South China Sea

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ABSTRACT

The past two millennia include some distinct climate intervals, such as the Medieval Warm Period (MWP) and the Little Ice Age (LIA), which were caused by natural forcing factors, as well as the Current Warm Period (CWP) that has been linked to anthropogenic factors. Therefore, this period has been of great interest to climate change researchers. However, most studies are based on terrestrial proxy records, historical documentary data, and simulation results, and the ocean and the tropical record are very limited. The Eastern Han, Three Kingdoms, and Western Jin periods (25–316 CE) cover the beginning first millennium CE in China, and were characterized by a cold climate and frequent wars and regime changes. This study used paired Sr/Ca and δ^{18}O series recovered from a fossil coral to reconstruct the sea surface water conditions during the late Eastern Han to Western Jin periods (167–309 CE) at Wenchang, eastern Hainan Island in the northern South China Sea (SCS), to investigate climate change at this time. The long-term sea surface temperature (SST) during the study interval was 25.1 °C, which is about 1.5 °C lower than that of the CWP (26.6 °C). Compared with the average value of 0.40‰ during the CWP, the long-term average seawater δ^{18}O (−0.06‰) was more negative. These results indicate that the climate conditions during the study period were cold and wet and comparable with those of the LIA. This colder climate may have been associated with the weaker summer solar irradiance. The wet conditions were caused by the reduced northward shift of the intertropical convergence zone/monsoon rainbelt associated with the retreat of the East Asian summer monsoon. Interannual and interdecadal climate variability may also have contributed to the variations in SST and seawater δ^{18}O recorded over the study period.

1. Introduction

Global warming has become the focus of increasing concern within the climate change research community over recent years. To better understand present-day climate conditions and the potential trend of future climate change, it is important to extend the temporal scale of investigation into the last two millennia (Taira, 1980; Fritz et al., 2000; Hu et al., 2001; Booth et al., 2006; Mann, 2007; Anderson et al., 2010; Tierney et al., 2010; Vuille et al., 2012; Consortium, 2013; Wurtzel et al., 2013; Denniston et al., 2015; Donnelly et al., 2015; H. Yan et al., 2015b). The importance of the last two millennia is that they include some distinct climate intervals. For example, climate anomalies such as the Medieval Warm Period (MWP, 900–1300 CE; Lamb, 1965; Crowley and Lowery, 2000; Bradley et al., 2003) and the Little Ice Age (LIA, 1550–1850 CE; Robock, 1979; Bradley and Jones, 1993; Matthews and Briffa, 2005) are believed to have been caused by natural forcing (e.g., solar variability and volcanic emissions). However, the Current Warm Period (CWP, 1850–present CE; Wu et al., 2012; Fleury et al., 2015) is a climate anomaly that has been linked with anthropogenic factors (e.g., industrialization and land-use changes).

In China, the problem of climate change over the past two millennia has been of longstanding interest to the paleoclimatic community (e.g., Gong and Hameed, 1991; Shi et al., 1999; Zheng et al., 2001; Yang et al., 2002, 2016; Ge et al., 2003, 2004, 2011; Holmes et al., 2009; Tan et al., 2011; Hao et al., 2012, 2016; Q. Ge et al., 2013; Q.S. Ge et al., 2013; H. Yan et al., 2015a; Q. Yan et al., 2015a, 2015b). However, almost all of these studies were based

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on terrestrial proxy records, historical documentary data, and simulation results. High-resolution ocean and tropical records are very limited; therefore, the full characteristics of the seasonal to annual climate over the past two millennia remain unclear.

The ocean plays an integral part in influencing the climate system and is intrinsically linked to the atmosphere through heat storage, global heat transportation, evaporation, freezing and thawing in polar regions, and gas storage and exchange (including CO_2; Herr and Galland, 2009). Therefore, climate change records from the ocean will undoubtedly improve our knowledge of the evolution of climate change over various periods. Massive coral is one of the most reliable proxies for climatic and environmental change in the ocean, as it contains clear annual bands and has high growth rates, thereby recording high-resolution climate information from the surrounding seawater in which it lived (Gagan et al., 2000; Lough, 2010). The Sr/Ca ratios preserved in coral skeletons have long been used to reconstruct changes in sea surface temperature (SST; Smith et al., 1979; Beck et al., 1992), and $\delta^{18}O$ values in coral reflect SST and $\delta^{18}O$ in the ambient seawater (Swart and Coleman, 1980; Dunbar and Wellington, 1981). Residual $\delta^{18}O$ (i.e., $\Delta\delta^{18}O$), which is calculated by subtracting the contribution of temperature from coral $\delta^{18}O$, can be used as a tracer for seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) and therefore salinity or rainfall (Mcculloch et al., 1994; Gagan et al., 1998, 2000; Corrège, 2006; Deng et al., 2009, 2014b; Deng and Wei, 2015).

As the largest marginal sea of the western Pacific, the climate in the South China Sea (SCS) is controlled by both the East Asian monsoon and the El Niño-Southern Oscillation (ENSO) over seasonal and interannual timescales, respectively (Yan et al., 2011a). Therefore, climate records from the SCS are important for the study of climate change over periods of significant change such as the MWP and LIA. In recent years, there have been a number of successful studies of past climate change based on coral records from the mid-Holocene to the CWP in the SCS (e.g., Sun et al., 2005; Yu et al., 2005; Wei et al., 2007; Liu et al., 2008, 2013; Deng et al., 2009, 2013, 2014b; Chiang et al., 2010; Yu, 2012; Chen et al., 2013; Deng and Wei, 2015; Yang et al., 2015). However, climate records that cover the past two millennia remain limited. In China, the Eastern Han, Three Kingdoms, and Western Jin periods (25–316 CE) mark the beginning of this period and were characterized by a cold climate and frequent wars and regime changes (Chu, 1973; Ge, 2011). Here, we use the paired Sr/Ca and $\delta^{18}O$ records from a fossil coral spanning the late Eastern Han through Western Jin dynasties to reconstruct the sea surface water conditions, including SST and hydrological characteristics, for eastern Hainan Island in the northern SCS. The differences between these periods and the CWP are compared to provide a new insight into climate change at the beginning of the first millennium CE, and a new benchmark for testing the reliability of climate models.

2. Materials and methods

A fossil coral (14FJ12) was collected from a *Porites lutea* colony on the fringing reefs at Fengjiawan, Wenchang, 2 km off the east coast of Hainan Island in the northern SCS (19°23′43.14″N, 110°45′11.16″E; Fig. 1). A modern coral (11LW4), for the comparative study, was collected in April 2011 at Longwan, Qionghai, which is also 2 km off the east coast of Hainan Island in the northern SCS (19°17′11.94″N, 110°39′21.06″E; Fig. 1). The two sampling sites are approximately 16 km apart. This modern coral has been used previously to study decadal variations in the northern SCS (Deng et al., 2013; Chen et al., 2015; Wei et al., 2015).

The fossil coral was dated by U-Th methods on a Nu Plasma multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) at the Radiogenic Isotope Laboratory, The University of Queensland. Details of the analysis method were described by Zhou et al. (2011).

The coral cores were first sectioned into slices of 1 cm thick and 5–7 cm wide. Then, X-ray photographs were taken to reveal the regular and well-defined annual density bands, which were used to establish the coral chronology. Next, the coral slices were soaked in 10% H_2O_2 for 24 h to remove organic matter, followed by ultrasonic cleaning in deionized water for 30 min to remove surface contaminates (Wei et al., 2007). Samples were collected at annual intervals along the main growth axis using a digitally controlled milling machine. X-ray diffraction (XRD) analyses of the samples showed that the coral skeleton was 100% aragonite. Scanning electron microscopy (SEM) imaging revealed that there was no secondary aragonite present in the coral skeleton.

Coral skeletal $\delta^{18}O$ and $\delta^{13}C$ analyses were performed using a GV Isoprime II stable isotope ratio mass spectrometer (IRMS) coupled with a MultiPrep carbonate device that used 102% H_3PO_4 at 90 °C to extract CO_2 from the coral samples, following the procedures described by Deng et al. (2009); the IRMS was located at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China. Isotope data were normalized to the Vienna Pee Dee Belemnite (V-PDB) using the NBS-19 standard ($\delta^{18}O = -2.20‰$, $\delta^{13}C = 1.95‰$). Multiple measurements on this standard yielded a reproducibility of 0.03‰ for $\delta^{13}C$ and 0.06‰ for $\delta^{18}O$. Replicate measurements were made on approximately 15% of the samples and their reproducibilities were comparable to that of the standard.

Analyses of Sr/Ca ratios were conducted on a Varian Vista Pro inductively coupled plasma atomic emission spectrometer (ICP-AES), in the same laboratory as that used for the stable isotope measurements. The standard reference material for calibration is the JCp-1 *Porites* sp. standard prepared by the Geological Survey of Japan (Okai et al., 2002). All Sr/Ca data were normalized to JCp-1 with $Sr/Ca = 8.838\ mmol\ mol^{-1}$ (Hathorne et al., 2013). Replicate analyses of an in-house *Porites* sp. coral standard solution BH-7 showed excellent reproducibility, with an external precision of 0.16%. Replicate measurements were made on approximately 15% of the samples and their reproducibilities were comparable to that of the in-house standard. See Wei et al. (2007) for a more detailed description of the Sr/Ca methodology.

Coral $\Delta\delta^{18}O$, a proxy for $\delta^{18}O_{sw}$, was calculated by subtracting the sea surface temperature (SST) contribution from the coral $\delta^{18}O$ values (Gagan et al., 1998), according to $\Delta\delta^{18}O = d\delta^{18}O/dT \times [T_{\delta18O} - T_{Sr/Ca}]$, where $d\delta^{18}O/dT$ is the slope of the empirical $\delta^{18}O$–SST function reported by Song et al. (2006), and $T_{\delta18O}$ and $T_{Sr/Ca}$ are the apparent SSTs calculated from $\delta^{18}O$ values and Sr/Ca ratios, respectively. We used the Sr/Ca–SST relationship reported by Gagan et al. (2012). This equation has been corrected for the apparent attenuation effect from the skeletal mass accumulation of coral. It is identical to the calibration using the annually resolved Sr/Ca ratios and instrumental SST records from the Great Barrier Reef (Deng et al., 2014a), thus it is suitable for calculating SST from annually resolved Sr/Ca ratios.

3. Results

The coral 14FJ12 was dated to 1712 ± 8 year BP, and this age was converted into its Common Era year giving a growing span of ca. 167–309 CE. This interval covers the late Eastern Han (167–220 CE), Three Kingdoms (220–265 CE), and Western Jin (265–316 CE) periods.

The variations of annual SST and seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$, coral $\Delta\delta^{18}O$) are presented in Fig. 2. The annual SST ranges from 23.5 to 26.3 °C, with a variation amplitude of 2.8 °C and an average of

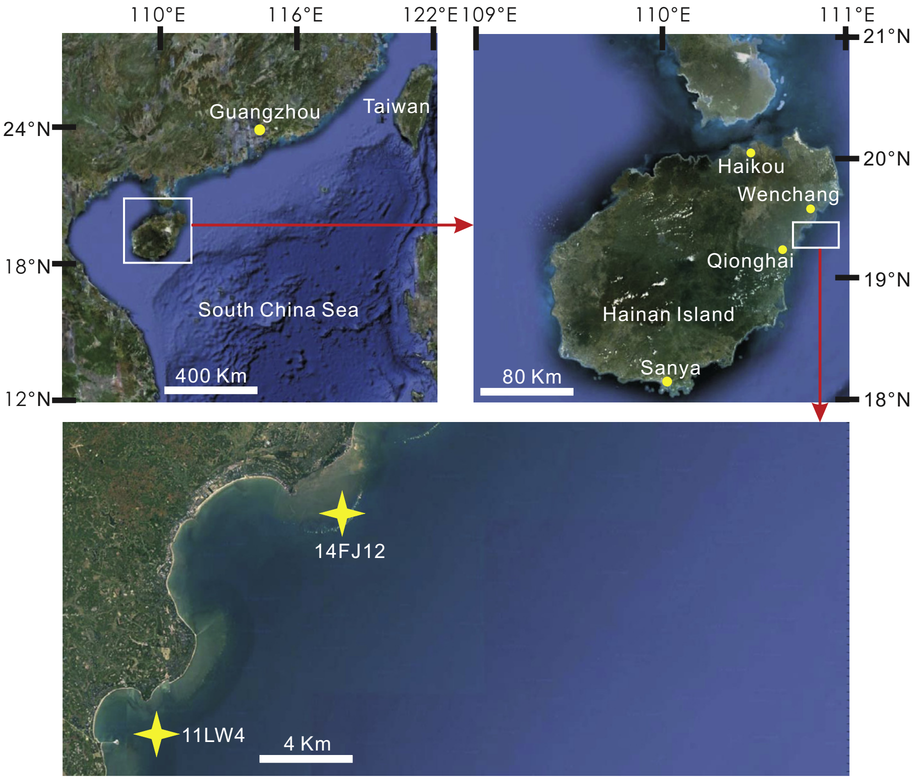

Fig. 1. Satellite image of Hainan Island. Yellow stars indicate sampling locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

25.1 °C (Fig. 2a). The average annual SST is 25.2 °C, 25.4 °C, and 24.6 °C for the late Eastern Han, Three Kingdoms, and Western Jin periods, respectively (Fig. 2a). The annual $\delta^{18}O_{sw}$ values range from −0.63‰ to 0.86‰, with a variation amplitude of 1.49‰ and an average of −0.06‰ (Fig. 2b). The average annual $\delta^{18}O_{sw}$ values are −0.05‰, −0.02‰, and −0.13‰ for the late Eastern Han, Three Kingdoms, and Western Jin periods, respectively (Fig. 2b). See the online supplementary dataset for additional details.

4. Discussion

4.1. The applicability of the coral records

The average of the annual SST records from 1870 to 2011 during the CWP were calculated by averaging the monthly SST, extracted from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1.1) dataset (http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdHadISST.html; Rayner et al., 2003) on a 1° × 1° grid centered on 19.5°N, 111.5°E (ca. 90 km from the sampling sites) is 26.0 °C. Instrumental records indicate that the average of the annual SST from 1960 to 1997 is 25.8 °C at Qinglan Harbor Meteorological Observatory, which is approximately 35 km from our sample sites. The average annual SST between 1853 and 2011 reconstructed from the coral Sr/Ca record is 26.6 °C. There are no long-term in situ instrumental SST data available that span the growth period of the modern coral (11LW4). Therefore, taking all possible error-inducing factors into account, including site differences, errors in the gridded data, instrumental error, and errors associated with the SST reconstruction, we believe that the SST records derived from coral Sr/Ca are reliable. In addition, all coral Sr/Ca data were normalized to the value of an international coral standard (JCp-1), and then transformed into SST records using the same Sr/Ca–SST thermometer. Another issue should be noted is the effect of summer upwelling on coral Sr/Ca record. Our study sites are exactly located in the areas affected by the summer upwelling system along the northeast coasts of Hainan Island (Jing et al., 2009; Liu et al., 2013), and the deep ocean water with an unusual Sr/Ca ratio may lead to an artifact in the Sr/Ca-SST calibration (de Villiers et al., 1994). The Sr/Ca-SST equation used here was based on the *Porites* corals from coastal upwelling area and laboratory culturing experiments and has been corrected for the attenuation effect by skeletal mass accumulation (Gagan et al., 2012). Therefore, it is reliable to act as a bridge to compare the SST difference between different time periods. In summary, we are confident that the average long-term reconstructed annual SST records are suitable for comparing and discussing SST trends over the study period.

There are no long-term in situ instrumental $\delta^{18}O_{sw}$ data available that span the growth period of the modern coral (11LW4). Gridded data and data from a nearby site are also unavailable. Therefore, it is difficult to discuss the absolute values of reconstructed $\delta^{18}O_{sw}$. Fortunately, the $\delta^{18}O_{sw}$ data extracted from the coral Sr/Ca and $\delta^{18}O$ are based on the same transfer equations and are normalized to the same reference standards as Sr/Ca and $\delta^{18}O$, and this makes it possible to study and compare the relative changes in $\delta^{18}O_{sw}$ over the different periods.

4.2. SST records from coral Sr/Ca

The annual SST from the late Eastern Han to Western Jin periods showed large fluctuations, varying between 23.5 and 26.3 °C. The climate during the Three Kingdoms dynasty was relatively warm, but the Western Jin was the coldest of the three periods under consideration here (Fig. 2a). Taking these three periods as a whole, the average value (25.1 °C) of long-term SSTs is about 1.5 °C lower than that of CWP (26.6 °C) obtained from the coral records (Fig. 3a). This

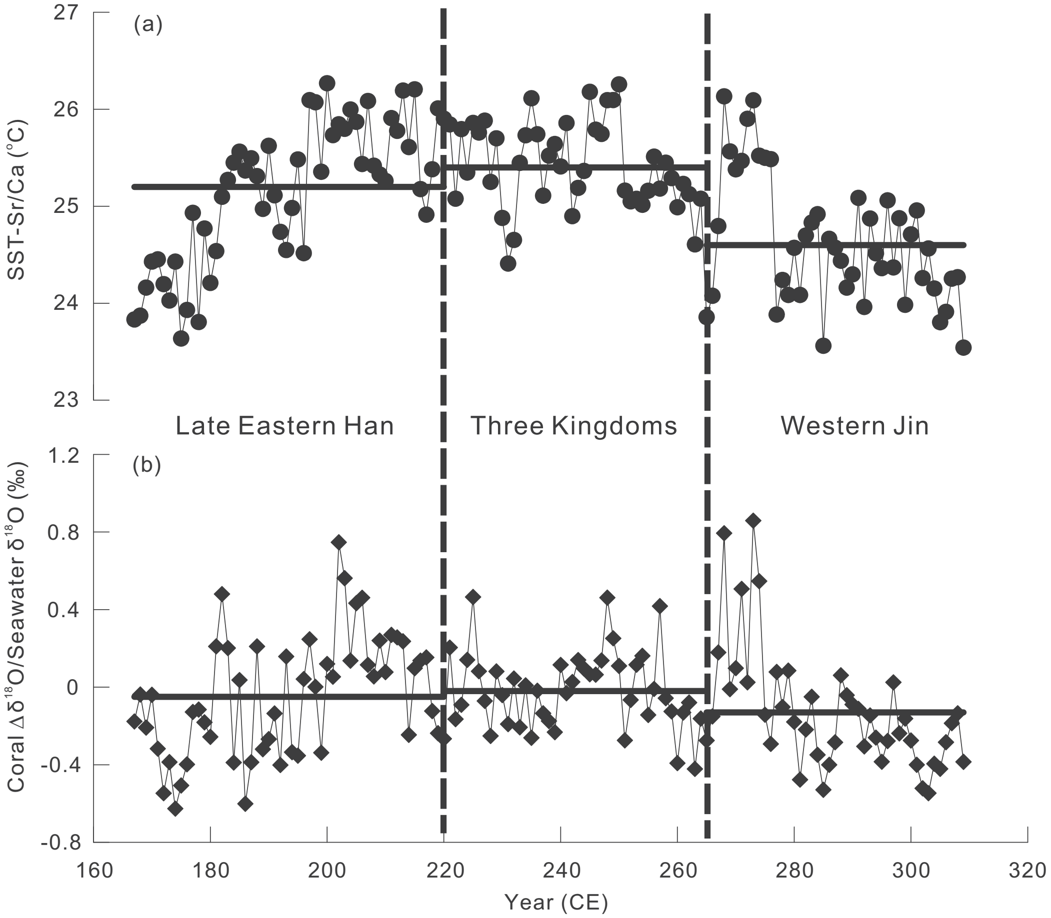

Fig. 2. Temporal variations of SST inferred from coral (a) Sr/Ca (dots) and (b) $\delta^{18}O_{sw}$ (diamonds) reconstructed from paired coral Sr/Ca and $\delta^{18}O$ during the late Eastern Han, Three Kingdoms, and Western Jin periods. Black horizontal lines indicate the averages of SST and $\delta^{18}O_{sw}$ for different periods.

SST difference between 167–309 CE and the CWP is even larger than that between 1455 ± 51 CE from the LIA and the present (1.08 °C) that was obtained from a giant clam record from the northern SCS (H. Yan et al., 2015a). Our coral records, together with the giant clam record, may indicate that the climate during the late Eastern Han to Western Jin periods was almost as cold as, or even colder than, that during the LIA. Chu's (1973) study demonstrated that the climate of the Wei-Jin Southern and Northern Dynasties (220–589 CE) was very cold, and the temperature over the period 280–289 CE was the lowest. Our coral records also record the coldest climate during the period 277–309 CE (Fig. 2a). The composite records also suggested that, over the past 2000 years, only the LIA was as cold as the Wei-Jin Southern and Northern Dynasties in eastern and central China (Ge, 2011).

There is no high-resolution SST record from the SCS and adjacent area covering our study period (25–316 CE), so a composite record established by combining ice cores, tree rings, lake sediments, and historical documents from the last two millennia was used for comparison with our coral record. This record indicated a cold interval around 240–800 CE in China (Yang et al., 2002). In spite of the difference between land and ocean temperatures, the discrepancy among the different proxy records, and the dating errors, the coral record displays a roughly similar trend with this composite record for the late Eastern Han to Western Jin periods (Fig. 4). This consistency may again confirm the reliability of the SST records reconstructed from coral geochemical proxies.

Climate change during the late Eastern Han to Western Jin periods was controlled primarily by natural forcing, such as solar radiation and volcanic eruptions (Baede et al., 2001). To assess the effects of the natural forcing on SST variability during these periods, we compared proxies for these forcing factors with our reconstructed SST record. For example, the residual atmospheric $\Delta^{14}C$ record is used to represent solar radiation, and a smaller $\Delta^{14}C$ corresponds to increased solar irradiance (Stuiver et al., 1998). Volcanic activity is indicated by the global volcanic aerosol forcing and the smaller forcing corresponds to stronger volcanic eruption (Sigl et al., 2015). However, the variations in atmospheric $\Delta^{14}C$ and global volcanic aerosol forcing did not match those of the SST record well (Fig. 5a and b), which may mean that the variations in SST did not respond linearly to forcing by solar irradiance and volcanic activity.

In addition to the above two forcing factors, the interactions between the atmospheric circulation and the land and ocean surfaces also play an important role in climate change (Baede et al., 2001). The strength of the Asian summer monsoon can be tracked using stalagmite $\delta^{18}O$ records (a more negative $\delta^{18}O$ indicates a stronger monsoon; Wang et al., 2005), and we also compared this with the reconstructed SST record. The co-variations between the SST reconstructed from coral Sr/Ca and the stalagmite $\delta^{18}O$ are much better than those between the SST and the solar and volcanic forcing factors (Fig. 5c). From this point, the summer monsoon appears to have been the principal control on long-term SST variability during the late Eastern Han to Western Jin periods. However, the modern meteorological and the paleoclimatic studies indicated that the strength of the summer monsoon has limited impact to the SST in SCS, while the changes of the winter monsoon

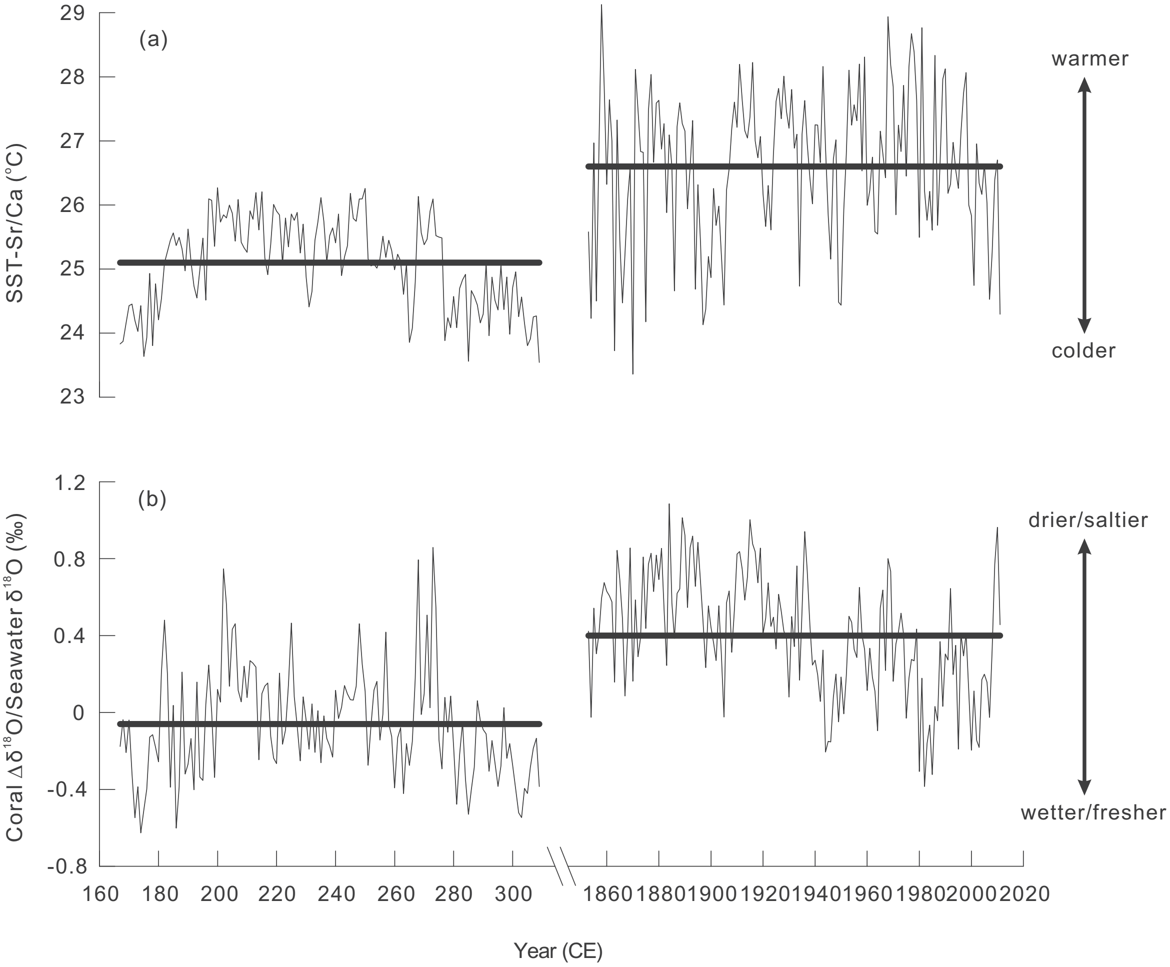

Fig. 3. Comparisons of (a) SST and (b) $\delta^{18}O_{sw}$ between the study interval (late Eastern Han to Western Jin periods) and the CWP. The black horizontal lines indicate the averages of SST and $\delta^{18}O_{sw}$ for the different periods.

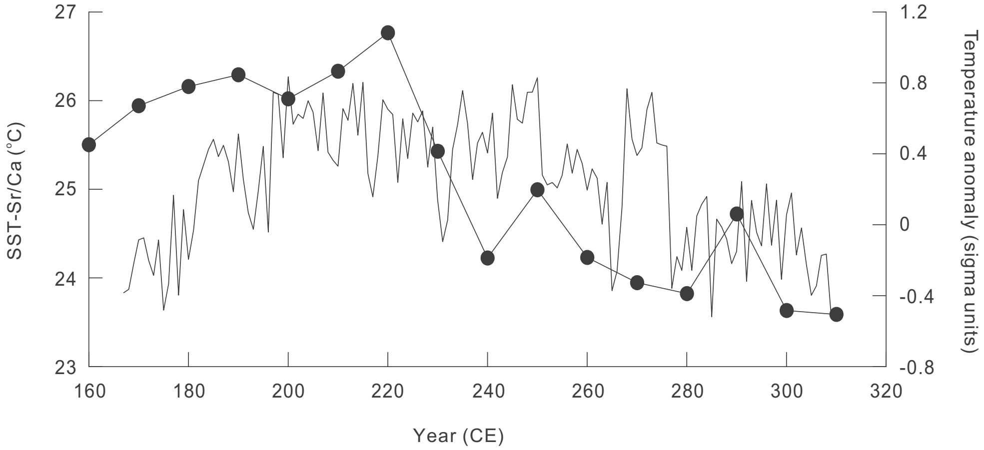

Fig. 4. Comparison of SST (solid line) and a composite temperature anomaly record (line with black dots) established by combining ice cores, tree rings, lake sediments, and historical documents over the late Eastern Han to Western Jin periods.

has a big contribution to the SST, especially in northern SCS (Wu and Chen, 2015; Zhang et al., 2016). The Holocene Asian summer monsoon is linked to the solar changes (Wang et al., 2005) so the co-variations between the annual coral-based SST and the stalagmite $\delta^{18}O$ may reflect that the weaker summer solar irradiance led to the colder SST seen over the century timescale at this time.

As for the ocean–atmosphere interactions, no instrumental or reconstructed records were available for comparison, but there were some signals of interannual (2–7 years) and interdecadal (11 years) variability in the SST record (Fig. 6a). The interannual signals probably record the signature of quasi-biennial and ENSO signals, as the interannual variability in the SCS is remotely influ-

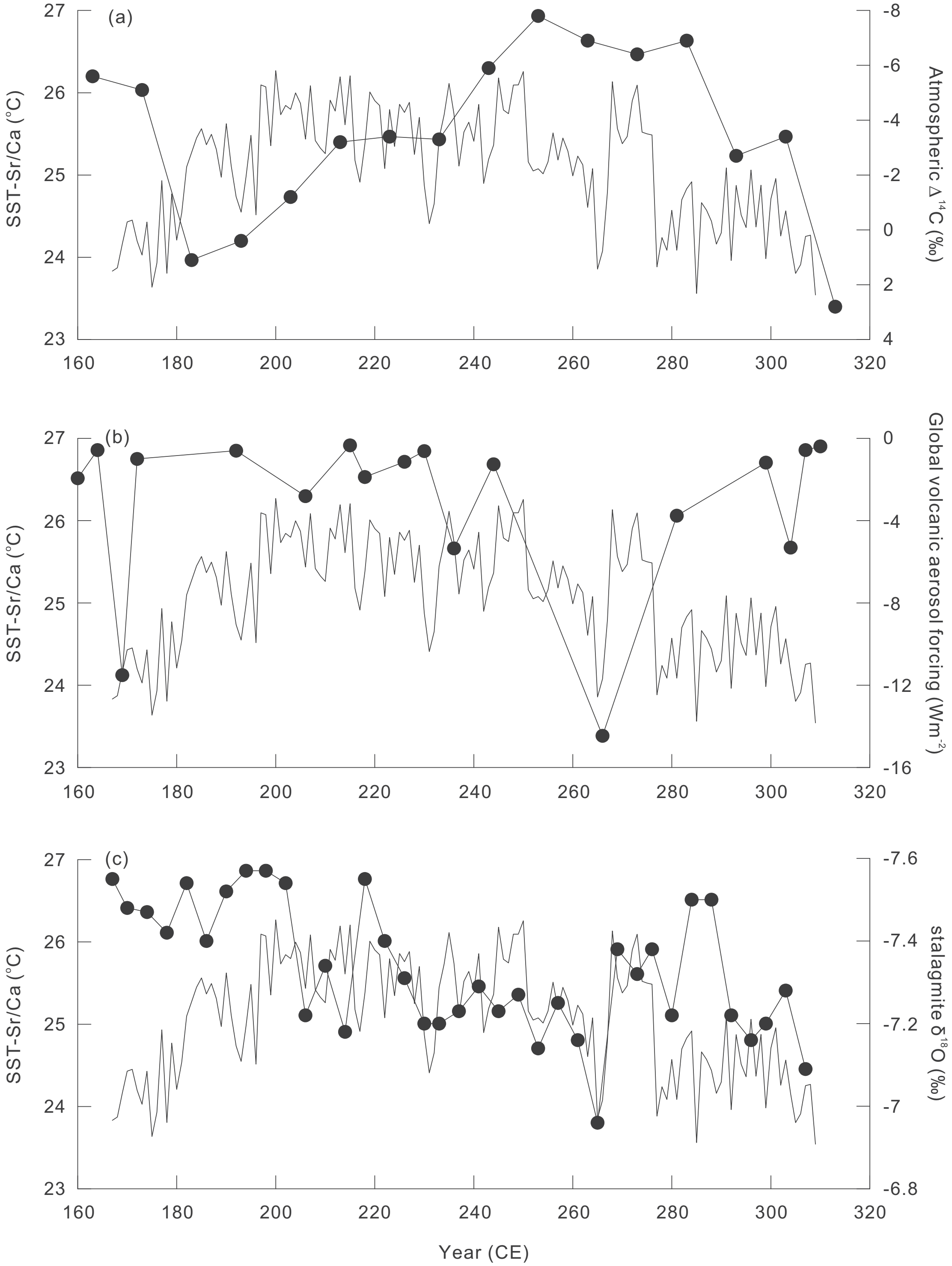

Fig. 5. Comparison of reconstructed SST (solid line) with the (a) residual atmospheric Δ^{14}C, (b) global volcanic aerosol forcing, and (c) stalagmite δ^{18}O records. Lines with black dots indicate the other three variables.

enced by ENSO (Liu et al., 2004, 2011; Wang et al., 2006). As a pattern of interdecadal climate variability in the North Pacific Basin, the Pacific Decadal Oscillation (PDO) has a widespread influence on surface climate, including on temperature and precipitation anomalies in the Pan-Pacific basin (Mantua and Hare, 2002; Gordon and Giulivi, 2004; Yang and Zhu, 2008; Mao et al., 2011). Therefore, these variabilities may suggest that ENSO and the PDO also affected the climate during the late Eastern Han to Western Jin periods in the northern SCS. The modern coral 11LW4 also recorded ENSO and PDO activity in the northern SCS (Deng et al., 2013).

4.3. $\delta^{18}O_{sw}$ records from coral Sr/Ca and $\delta^{18}O$

The $\delta^{18}O_{sw}$ was stable during the three periods studied here, and the average annual $\delta^{18}O_{sw}$ during the Western Jin (−0.13‰)

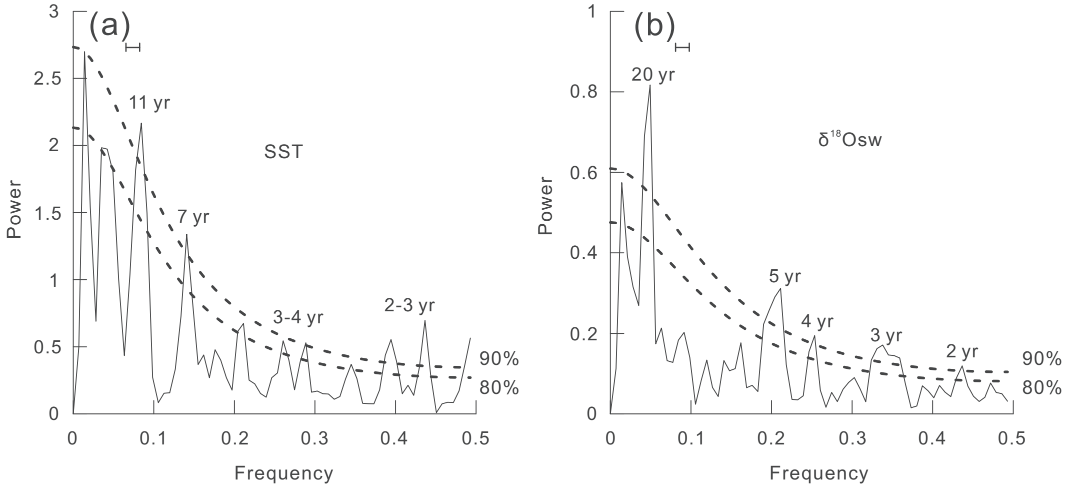

Fig. 6. Power spectra of (a) SST and (b) $\delta^{18}O_{sw}$ from coral records calculated using the software PAST (Hammer et al., 2001). The numbers indicate the possible periodicities. The horizontal bars indicate the bandwidths, and the dashed lines indicate the 90% and 80% confidence levels.

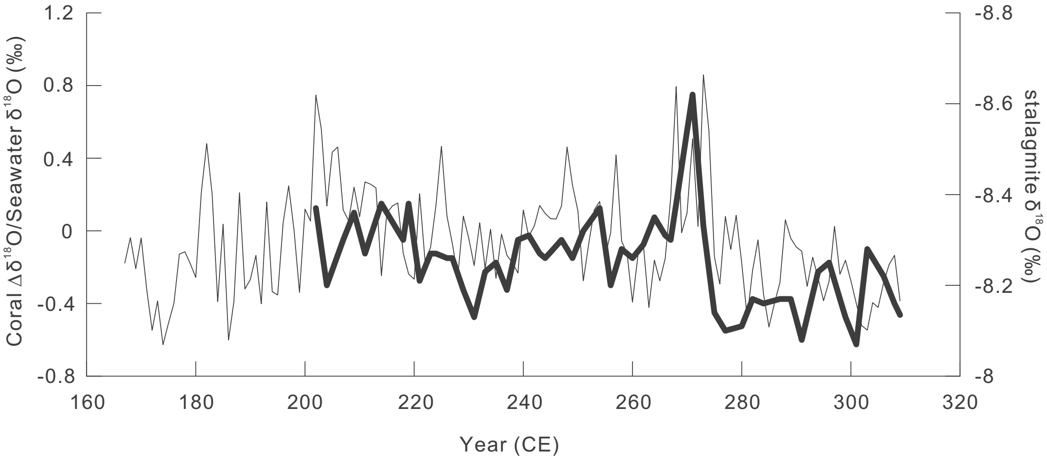

Fig. 7. Comparison between $\delta^{18}O_{sw}$ (thin line; reconstructed from the paired coral Sr/Ca and $\delta^{18}O$) and the stalagmite $\delta^{18}O$ record from northern China (thick line).

was slightly lower than during the late Eastern Han (−0.05‰) and the Three Kingdoms (−0.02‰; Fig. 2b). This difference indicates that the seawater during the Western Jin period was the coldest and freshest of these three periods. Compared with the average long-term $\delta^{18}O_{sw}$ in the CWP (0.40‰), the $\delta^{18}O_{sw}$ was more negative during the late Eastern Han to Western Jin periods (Fig. 3b). The difference of about 0.40‰ corresponds to a difference of about 2.0 in sea surface salinity as estimated from the relationship between salinity and $\delta^{18}O_{sw}$ in the northern SCS (Ye et al., 2014). Therefore, the coral records indicate cold and wet climate conditions during the Late Eastern Han to Western Jin periods. The climate conditions during these three periods were very similar to those during the LIA. Some previous studies have suggested a wet LIA in tropical southern China and the northern SCS (Yan et al., 2011b; Zeng et al., 2012; Wang et al., 2013).

As there are no high-resolution $\delta^{18}O_{sw}$ records available from the SCS and adjacent areas for these periods, we compared a stalagmite $\delta^{18}O$ record from Wanxiang Cave (in Gansu Province, northern China; Zhang et al., 2008) with our coral record. This stalagmite $\delta^{18}O$ record, together with a record based on lake sediments and ostracod shells in the SCS, has been used to study the intertropical convergence zone (ITCZ) over the western Pacific during the LIA, and the results indicated a dry LIA in northern China, but a wet LIA in the SCS (H. Yan et al., 2015b). Considering the climatic similarity between our study interval and the LIA described above, this stalagmite $\delta^{18}O$ record was used for our comparative study. The stalagmite $\delta^{18}O$ record was linearly interpolated to an annual resolution and then compared with the annually resolved coral $\Delta\delta^{18}O$ record. We found that the coral $\delta^{18}O_{sw}$ series and the stalagmite $\delta^{18}O$ record are anti-correlated ($r = -0.40$, $n = 108$, $p < 0.0001$) and follow a similar variational trend (Fig. 7). Their anti-correlation may suggest that the hydrological conditions in northern China and in the SCS were opposite at the annual timescale during the late Eastern Han to Western Jin periods, which is similar to the situation at these two study sites at the century timescale during the LIA as indicated by H. Yan et al. (2015b). The reduced northward shift of the ITCZ/monsoon rainbelt by the retreat of the East Asian summer monsoon (EASM) may have led to relatively dry conditions in the north, but more rainfall in tropical southern China and the northern SCS. The EASM was relatively weaker during the late Eastern Han to Western Jin periods according to the stalagmite $\delta^{18}O$ record (Wang et al., 2005). Therefore, the wet conditions at this time seen over the century timescale may also be associated with the contraction of the ITCZ/monsoon zones within the western Pacific accompanied by the retreat of the EASM (H. Yan et al., 2015b). Regarding the opposite hydrological conditions at the annual timescale, further study, especially numerical modeling, is needed to clarify whether or not this is associated with the retreat of the EASM. There are also interannual (2–5 years) and interdecadal (20 years) variabilities in the $\delta^{18}O_{sw}$ (coral $\Delta\delta^{18}O$) record (Fig. 6b), which may indicate the effect of ENSO and the PDO on hydrological conditions.

5. Conclusions

Based on geochemical records from paired Sr/Ca and $\delta^{18}O$ preserved in a fossil coral whose growing period covered the late Eastern Han, Three Kingdoms, and Western Jin periods, we reconstructed the sea surface conditions, including temperature and hydrological conditions, during these periods in the northern SCS. Our main conclusions are as follows.

(1) The annual SSTs from the late Eastern Han to Western Jin periods showed large fluctuations: from 23.5 to 26.3 °C. The average long-term SST during the study period was 25.1 °C, which is about 1.5 °C lower than that during the CWP.
(2) $\delta^{18}O_{sw}$ was stable during the three periods, and the average long-term annual $\delta^{18}O_{sw}$ (−0.13‰) was more negative than that over the CWP. This difference suggests wet/fresher hydrological conditions during the late Eastern Han to Western Jin periods.
(3) The climatic conditions during the late Eastern Han to Western Jin periods were cold and wet in the northern SCS, which is comparable with conditions during the LIA. The cold climate may be associated with the weaker summer solar irradiance. The wet conditions were caused by the reduced northward shift of the ITCZ/monsoon rainbelt associated with the retreat of the EASM. ENSO and the PDO may have also contributed to the interannual and interdecadal variabilities in the SST and $\delta^{18}O_{sw}$ records.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2016.12.012.

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