https://doi.org/10.5194/cp-2019-54
Preprint. Discussion started: 3 June 2019

Climate of the Past
Discussions
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Evidence of intense climate variation and reduced ENSO activity from $\delta^{18}O$ of *Tridacna* 3700 years ago

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Abstract

Tridacna is the largest marine bivalves in the tropical ocean, and its carbonate shell can shed light on high-resolution paleoclimate reconstruction. In this contribution, $\delta^{18}O_{shell}$ was used to estimate the climatic variation in the Xisha Islands of the South China Sea. We first evaluate the sea surface temperature (SST) and sea surface salinity (SSS) influence on modern rehandled monthly (r-monthly) resolution *Tridacna gigas* $\delta^{18}O_{shell}$. The obtained results reveal that $\delta^{18}O_{shell}$ seasonal variation is mainly controlled by SST and appear insensitive to local SSS change. Thus, the $\delta^{18}O$ of *Tridacna* shells can be roughly used as a proxy of the local SST: a 1 ‰ $\delta^{18}O_{shell}$ change

https://doi.org/10.5194/cp-2019-54
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is roughly equal to 4.41 °C of SST. R-monthly $\delta^{18}O$ of a 40-year *Tridacna squamosa* (3673 ± 28 BP) from the North Reef of Xisha Islands was analyzed and compared with the modern specimen. The difference between the average $\delta^{18}O$ of fossil *Tridacna* shell ($\delta^{18}O$ = -1.34 ‰) and modern *Tridacna* specimen ($\delta^{18}O$ = -1.15 ‰) probably implies a warm climate with roughly 0.84°C higher in 3700 years ago. The seasonal variation in 3700 years ago was slightly decreased compared with that suggested by the instrument data, and the switching between warm and cold-seasons was rapid. Higher amplitude in r-monthly and r-annual reconstructed SST anomalies implies an enhanced climate variability in this past warm period. Investigation of the El Ninõ-Southern Oscillation (ENSO) variation (based on the reconstructed SST series) indicates a reduced ENSO frequency but more extreme El Ninõ events in 3700 years ago.

Key words: *Tridacna*; $\delta^{18}O$; South China Sea; Seasonal variation; Climate variation; ENSO activity

1 Introduction

Carbonate skeleton of marine organisms, such as corals, foraminifers, mollusks, have been widely used to reconstruct environmental variation (Aharon, 1983; Batenburg et al., 2011; Ourbak et al., 2006; Schöne et al., 2005; Wanamaker et al., 2011; Yoshimura et al., 2016; Yu et al., 2005). Due to their high sensitivity to the surrounding environment and the ability to preserve of high-resolution physicochemical variations in their skeleton, these marine biogenic carbonates can shed light on the past climate dynamics. *Tridacna* species, as the largest bivalves and usually live in tropical coral reefs, have received increasing scientific attention in the recent decades (Pätzold et al., 1991; Watanabe et al., 1999; Watanabe et al., 2004; Elliot et al., 2009; Ayling et al., 2015). This is because these bivalves and their shells have many favorable properties for recording local environmental changes: they have dense and well-preserved aragonite shells, fast growth rates (up to 1 cm/yr) with clear annual growth lines, and with longevity from several decades to a few centuries. These advantages make *Tridacna* an ideal material for high-resolution reconstruction of interannual, seasonal or even sub-seasonal climatic variations.

Previous studies indicated that *Tridacna* species precipitate their shells with the oxygen

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isotopic ($\delta^{18}O$) equilibrium with seawater (Aharon, 1991; Aharon and Chappell, 1986; Pätzold et al., 1991; Romanek and Grossman, 1989; Watanabe et al., 1999), and the influence of ontogenic reduction on the *Tridacna* $\delta^{18}O$ is negligible (Welsh et al., 2011). These studies implied that $\delta^{18}O_{shell}$ can be used to reconstruct the late Quaternary Sea-level and climatic changes. Indeed, $\delta^{18}O$ of marine biogenic carbonates are not only influenced by sea surface temperature (SST) but also by surrounding seawater $\delta^{18}O$. Meanwhile, seawater $\delta^{18}O$ have a close correlation with sea surface salinity (SSS), which is affected by tropical evaporation and precipitation balance. Nonetheless, the SST and SSS influence on $\delta^{18}O_{shell}$ is uncertainties due to the distinct variation of temperature and salinity in different area. For example, $\delta^{18}O_{shell}$ of the *Tridacna* from southwestern Japan could be directly used as a proxy of SST (Yamanashi et al., 2016), while $\delta^{18}O_{shell}$ of Indonesian *Tridacna* were interpreted to be contributed 71.4 % by SST and 28.6 % by SSS (Arias-Ruiz et al., 2017). Thus, local calibration from modern *Tridacna* is important to determine the relationship of $\delta^{18}O_{shell}$, SST and SSS.

Climatic variation in the Meghalayan (began at 4200 BP in late Holocene) has significant impacts on human society and ecosystem development. However, the early Meghalayan climatic conditions in SE Asia around the South China Sea still remain poorly understood. Shi (1994) reviewed the data from various sources (like ice core, inland lakes, paleosols in loess and eolian sands, sea level fluctuations, palynological and botanical studies) in China, indicating the early Maghalayan was involved in Holocene Megathermal period (8 to 3 ka BP). Sediments in the South China Sea also implied the temperature may have been relatively higher in the early of Meghalayan than present (Ouyang et al., 2016). However, those studies are low- resolution, the high-resolution records under interannual climate variation are rare. With global warming and many climatic disasters occur nowadays, the climatic conditions in the early Meghalayan could serve as an analogue to the modern problems, and have received increasing scientific attention (Schirrmacher et al., 2019; Scuderi et al., 2019; Toth and Aronson, 2019; Zhang et al., 2018). High-resolution isotopic geochemical data on the *Tridacna* in this period become an insight into the climatic variations, including extreme ones.

Furthermore, the El Ninõ-Southern Oscillation (ENSO) is widely accepted to be a main trigger for interannual climatic variability in the Pacific Ocean. Previous studies suggested that the

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impacts of ENSO activity would not be limited to the tropical area, but also on the global atmospheric circulation through heating-up of the tropical atmosphere (Cane, 2005). A fragmentary understanding of the ENSO dynamics causes the uncertainties to predict current or future variation. Many published models of ENSO behavior (on the average climate and background of the tropical Pacific) were constructed with low-resolution proxy data (Clement et al., 1999), so it seems seasonal or monthly data are important to examine the precise variation in ENSO activity. Recent studies on the late Holocene ENSO evolution yielded controversial findings: Coral records from the tropical Christmas Island showed a reduced ENSO variability around the late Holocene (McGregor et al., 2013; Woodroffe et al., 2003), yet some other studies indicate strengthening ENSO activity at 4 to 3 ka BP (Tudhope et al., 2001; Duprey et al., 2014; Yang et al., 2019). Thus, this further points to the importance of high-resolution isotopic geochemical data in unraveling the dynamics of ENSO from the local to global scale.

This study aims to evaluate the seasonality, climate variation, and ENSO activity in the Xisha Islands of the northern South China Sea, based on two high-resolution $\delta^{18}O_{shell}$ profiles of modern and fossil *Tridacna*. The study area situated in the northwest margin of the West Pacific Warm Pool (WPWP), and the local climate is widely accepted to be directly responsive to ENSO activity (Mitsuguchi et al., 2008; Yan et al., 2010). A modern *Tridacna gigas* shell was first to estimate the extent of environmental control (SST and SSS) on $\delta^{18}O_{shell}$, and a new SST-$\delta^{18}O_{shell}$ linear regression was proposed. Subsequently, a 40-year fossil *Tridacna squamosa* was used to reconstruct the seasonality and climatic variation, and the obtained results are compared with the modern species and meteorological observations. Finally, the ENSO activity and extreme El Ninõ events were discussed, using the re-established SST anomalies.

2 Materials and methods

2.1 Regional setting

The South China Sea is located in the northwest of WPWP (Fig. 1a), and its interannual climate has a close relation to ENSO activities (Mitsuguchi et al., 2008; Yan et al., 2010). The Xisha Islands in the northern South China Sea (300 km south of Hainan Island) is substantially influenced by two contrasting Asian monsoons from opposite directions: The Asian summer

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monsoon from the southwest and the Asian winter monsoon from the northeast. These two monsoons give distinct seasonal SST to the *Tridacna* from the coral reefs of the Xisha Islands. Our sample (*Tridacna squamosa* A5) was collected in the North Reef (17°05´ N, 111°30´ E), whilst the modern *Tridacna gigas* sample YX1 (studied previously by Yan (2013)), was acquired from the Yongxing Island (16°50´ N, 112°50´ E), which is about 90 kilometers away from the North Reef (Fig. 1a).

Meteorological observations (atmosphere temperature (AT), SST, SSS, rainfalls) are obtained from the Institute of Meteorology of China in the Xisha Islands since 1958. Due to the minimum number of YX1 in a year is seven, the time-scale of modern *Tridacna* YX1 is rehandling into seven points/yr, which indicates a rehandled month (r-month) represents 1.7 actual month. All meteorological observations and $\delta^{18}O_{shell}$ are using this method to rehandle the time-scale. Figure 1d shows the r-monthly-average time series of AT, SST, SSS, rainfall and their standard deviations (SD). The mean SST is 27.77 °C, AT show a highly positive correlation with SST (r=0.98), but is 0.7 °C lower. The SST seasonality is 5.33 °C, with the lowest value and highest value occurring in 1st r-month and 4th r-month, respectively. The Xisha Islands are far from the continent river runoff can hardly influence on SSS. SSS change from 33.25 to 33.81 ‰, and the change is mainly dominated by rainfall: higher SSS in dry winter and lower SSS in wet summer (Fig. 1e).

The SST data in the North Reef are acquired from NOAA HadISST, a global monthly SST data with a spatial resolution of 1° × 1° (data grid cell of data includes both the North Reef and the Yongxing Island) from 1982 to 2017. Ninõ 1 + 2 SST are obtained from NOAA monthly data between 1982 to 2017 (http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices).

2.2 Shell descriptions and sample preparation

The 29 cm long fossil *Tridacna squamosa* A5 was cut from the umbo to the ventral margin along the axis of maximum growth (Fig. 1b). A 5 mm-thick slice reveals three different zones (Fig. 1c): the inner layer, outer layer and the hinge. The inner layer is chosen for the analyses because of its clear growth layer and well-preserved shell. Published data also revealed that the inner layer $\delta^{18}O$ values were unaffected by different growth rates or ontogeny (Welsh et al., 2011), and could better reflect actual $\delta^{18}O$ than the inner layer or the hinge (Pätzold et al., 1991; Elliot et al., 2009).

The ^{14}C AMS test revealed the fossil *Tridacna* gigas age was 3437 ± 28 BP. For the

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marine-reservoir effect, the conventional radiocarbon age was 3673 ± 28 BP using the Radiocarbon Calibration Program CALIB 7.10 (http://calib.org). Both X-ray diffraction (XRD) and laser Raman spectrometers results were aragonite, no other substances were found.

2.3 Stable isotopes

Stable isotope samples were micromilled perpendicular to the growth layer under the micro-drill automated system (Micro-Drill New Wave Research, Olympus SZ 61) in the Isotope Laboratory of Xi'an Jiaotong University, China. Each sample was performed under 1 mm long, 100 μm deep. Four intervals were used according to the growth rates: 100 μm (n = 1 to 268), 150 μm (n = 269 to 481), 200 μm (n = 482 to 657), 300 μm (n = 658 to 765) respectively from adult to childhood (Fig. 2).

$\delta^{18}O$ of *Tridacna* was analyzed in the Isotope Laboratory of Xi'an Jiaotong University, using the ThermoFinnigan MAT-253 mass spectrometer fitted with a Kiel Carbonate Device IV. All the results were reported in per mil (‰), relative to the Vienna PeeDee Belemnite (VPDB) standard. The international standard TTB_1 were added to the analyses every 10 to 20 samples to check the reproducibility. Duplicate measurements of TTB_1 standards and samples showed a long-term reproducibility (1σ) of less than 0.14 ‰ and 0.05 ‰, respectively.

Published data of the modern *Tridacna* gigas shell YX1 were used to investigate the relationship between *Tridacna* $\delta^{18}O$ and local climate (Yan et al., 2013). YX1 was collected from the Yongxing Island, 120 km ESE of the North Reef (Fig. 1b). Modern *Tridacna* YX1 $\delta^{18}O$ (VPDB) of internal carbonate standard (GBW04405) is of (average) -8.49 ± 0.14 ‰, and the standards and samples have reproducibility (1σ) of better than 0.08 ‰ and 0.06 ‰, respectively. The average $\delta^{18}O$ (VPDB) TTB1 (A5) is also of -8.49 ± 0.14 ‰, which would minimize deviation during comparison.

2.4 Data processing and analyses

PearsonT3 (Version 2.2, January 2017) was used to test the correlation coefficient. Monthly insolation was calculated in 100 years by AnalySeries 2.0.8 (Laskar et al., 2004), which contained the calculated sigmas of conventional radiocarbon age in *Tridacna* (A5) life span. The years of modern insolation range from 1918 to 2017, and the time-scale of *Tridacna* A5 range from 3722 to 3623 BP. Statistical analyses were performed with software of Origin 2018 and PAST 3.18. Since the yearly minimum number in $\delta^{18}O_{YX1}$ was seven, thus the isotopic records, climatic data and insolation data were rehandled to seven points/yr with the AnalySeries 2.0.8 (Schöne and Fiebig, 2009; Wanamaker et al., 2011). This sclerochronologic rehandling would decrease the growth rates deviation.

3 Results

3.1 $\delta^{18}O_{A5}$ record

Seasonal cycles are distinct in the $\delta^{18}O_{A5}$ profile (Fig. 2), which show the 40 years of which the *Tridacna* had lived. The $\delta^{18}O_{A5}$ range from -2.07 to -0.14 ‰ (mean -1.35 ‰, n=765). After rehandling into 7 points/yr, $\delta^{18}O_{A5}$ vary from -1.98 to -0.29 ‰ (mean -1.34 ‰, n=281).

3.2 Sclerochronology

From the shell slice section, 40 dark/light couples (each representing one year) can be seen clearly. Higher $\delta^{18}O_{A5}$ values lie in the short dark increments (transparent), corresponding to the low temperature and dry seasons. In contrast, lower $\delta^{18}O_{A5}$ values lie in the long light increments (opaque), corresponding to the high temperatures and wet seasons (Fig. 3a).

Annual growth rates can be calculated with the $\delta^{18}O_{A5}$ seasonal cycles and interval distance (Fig. 3b). The results show that growth rates were higher when *Tridacna* A5 was young, reaching 5 mm/yr. The growth then slowed down and stabilized to 1-2 mm/yr after the *Tridacna* had grown mature. Furthermore, daily increments are obvious under the microscope (Fig. 3b). In general, *Tridacna* A5 grew faster in warm seasons and slower in cold seasons (Fig. 3b).

The SST observation in the Xisha Islands suggested that the 1st r-month corresponds to almost the lowest SST. Thus, the highest $\delta^{18}O$ of each cycle was chosen to be the beginning of a year. After the data rehandling, the potential deviation in different growth rates can also be reduced.

4 Discussion

4.1 Relation of SST, SSS and $\delta^{18}O$ of modern Tridacna

Previous studies demonstrated that *Tridacna* is in isotopic equilibrium with the surrounding seawater (Aharon, 1983; Watanabe et al., 1999), which also holds true for the *Tridacna* in the

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South China Sea (Yan et al., 2013). Biogenic carbonate $\delta^{18}O$ values are in linear correlations with the SST and seawater $\delta^{18}O_{water}$ (Aharon and Chappell, 1986; Pätzold et al., 1991; Romanek and Grossman, 1989). We adopted the $\delta^{18}O_{shell}$-SST-$\delta^{18}O_{water}$ Eq. (1) of Grossman and Ku (1986), which is widely used in calculations for tropical aragonite mollusk species. Meanwhile, $\delta^{18}O_{water}$ has a positive relationship to SSS, thus, $\delta^{18}O_{water}$ can be estimated with Eq (2) which is established through seawater in the northern South China Sea (Hong et al., 1997). We merged Eq (1) and (2) into $\delta^{18}O_{shell}$-SST-SSS (Eq (3)), and used two approaches to discuss the extent of SST and SSS influence on $\delta^{18}O_{YX1}$ under different time-scale.

$$SST\ (°C) = 21.8 - 4.69\ (\delta^{18}O_{shell} - \delta^{18}O_{water}) \quad (1)$$

$$\delta^{18}O_{water}\ (‰) = 0.23 \times SSS - 7.58 \quad (2)$$

$$SST\ (°C) = -13.75 - 4.69 \times \delta^{18}O_{shell} + 1.08 \times SSS \quad (3)$$

In the first approach (seasonal time-scale), we hypothesized two conditions: one with constant SSS but varying SST, and the other with constant SST but varying SSS. Two $\delta^{18}O$ profiles can be calculated: $\delta^{18}O_{SST}$ (under constant SSS) and $\delta^{18}O_{SSS}$ (under constant SST) (Fig. 4a). R-monthly mean values were used to minimize the influence of extreme events. The $\delta^{18}O_{YX1}$, $\delta^{18}O_{SST,}$ and $\delta^{18}O_{SSS}$ values are of -0.57 to -1.52 ‰, -0.48 to -1.58 ‰, -1.07 to -1.19 ‰, respectively. The $\delta^{18}O_{SSS}$ variation is only 0.12 ‰, 14 % of the $\delta^{18}O_{YX1}$ variation. The correlation between $\delta^{18}O_{YX1}$ and $\delta^{18}O_{SST}$ is high ($r = 0.91$, $n = 7$; $r = 0.78$, $n = 77$), and the two $\delta^{18}O$ profiles show the same trend. This indicates that $\delta^{18}O_{shell}$ in the Xisha Islands correspond predominantly to the seasonal SST variation.

In the second approach (based on Eq (1) and (2)), the calculated $\delta^{18}O_{predicted}$ (by using both actual SST and SSS) were used to compare with $\delta^{18}O_{YX1}$ (Table S1). The $\delta^{18}O_{YX1}$ and $\delta^{18}O_{predicted}$ profiles have nearly the same mean value (1.15 ‰ and 1.14 ‰, respectively) and indicate a perfect match ($r = 0.81$, $n = 77$). This confirms that the local *Tridacna* precipitates its shell in oxygen isotopic equilibrium. In order to determine whether the SSS variation in different season affect the predicted SST significantly, we use the actual SSS, constant SSS (mean SSS) and $\delta^{18}O_{YX1}$ to calculate predicted SST. Two predicted SST values (one calculated with varying SSS and the other with constant SSS) have high similarity ($r = 0.93$) (Fig. 4e), and they correspond to the variation of actual SST. Each of these predicted SST values is well correlated with the actual

SST (r_{vary} = 0.79, $r_{constant}$ = 0.78). This means that the SSS has little influence on the seasonal $\delta^{18}O_{shell}$ variation. Thus, we can then use $\delta^{18}O_{shell}$ to roughly estimate the seasonal local SST variation, and establish a new SST-$\delta^{18}O_{shell}$ linear regression: SST (°C) = 22.69 - 4.41 × $\delta^{18}O_{shell}$ (or $\delta^{18}O_{shell}$ (‰) = -0.136 × SST + 2.634). A 1 ‰ change of $\delta^{18}O_{shell}$ is roughly equal to 4.41°C of SST. Yu (2005) summarized the published δ^{18}O-SST slopes for the *Porites lutea* coral from different places, and suggested that the slopes range from -0.134 to -0.189, in which our result lies (-0.136). In addition, corals from Hainan Island revealed a good δ^{18}O vs. SST correlation with a linear regression slope of -0.137 (Su et al., 2006), very similar to our result. Consequently, it is reliable to use the new linear regression for reconstructing the past SST with the fossil $\delta^{18}O_{shell}$.

4.2 Indication of seasonal variation in modern Tridacna

From both $\delta^{18}O_{YX1}$ (-0.60 to -1.52 ‰) and $\delta^{18}O_{predicted}$ (-0.47 to -1.57 ‰) profiles (Fig. 4b), clear seasonality in shown with the lowest value occurring in the 1st r-month (cold seasons) and the highest value in the 4th r-month (warm seasons). Variance in $\delta^{18}O_{YX1}$ seasonality is 0.19 % shorter than $\delta^{18}O_{predicted}$, which may be due to the different growth rates and equidistance sampling mode. In each year, the analyzed *Tridacna* grew faster in warmer seasons than in colder seasons, thus, specimens under equidistance sampling mode would have more samples in the warm seasons. Fewer points in the cold seasons would decrease the values and lead to lower $\delta^{18}O_{shell}$ in the 1st r-month, but the higher number of points make $\delta^{18}O_{shell}$ close to $\delta^{18}O_{predicted}$ in the warm seasons (nearly identical in the 4th r-month. Moreover, throughout the life of the analyzed *Tridacna*, the $\delta^{18}O_{shell}$ amplitude is more approached to the actual $\delta^{18}O_{predicted}$ under higher number of points (high growth rates) before it reached maturity. After the *Tridacna* reach maturity, the fewer points taken in a year yielded a lower amplitude. This can explain the minor discrepancy between $\delta^{18}O_{shell}$ and $\delta^{18}O_{predicted}$. As a result, $\delta^{18}O_{shell}$ would slightly reduce the actual seasonal variation. However, the correlation between them is high (r = 0.81, n = 77), and the mean of $\delta^{18}O_{YX1}$ (-1.15 ‰) and $\delta^{18}O_{predicted}$ (-1.14 ‰) values are similar. Therefore, $\delta^{18}O_{shell}$ can also be used to estimate the actual seasonal variation, with caution to the slightly reduced variation.

4.3 Reconstructed climate with fossil Tridacna A5 $\delta^{18}O$ evidence

The fossil *Tridacna* lived in 3700 years ago during the early Meghalayan. The 40 $\delta^{18}O_{A5}$ cycles reveal that *Tridacna* A5 had probably lived for at least 40 years. After calculating data into

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r-monthly average profiles, the extreme seasonal variation effects were minimized. The mean $\delta^{18}O_{A5}$ profiles is -1.34 ‰, with the minimum and maximum of -1.66 and 0.66 ‰, respectively (Fig. 4c). Contrasting to the mean value of YX1 (-1.15 ‰), the lower $\delta^{18}O_{A5}$ mean value may have reflected the higher temperature in which the *Tridacna* had lived. To translate into SST (without considering the SSS changes), the temperature was estimated to be roughly 0.84°C higher than present. This agrees with other lines of evidence that suggested a higher temperature during that period (Ouyang et al., 2016), which was considered to be a Holocene Megathermal in China (8.5 to 3 ka BP) (Shi et al., 1992).

The average r-monthly seasonal range of this period (1 ‰) is similar to that yielded from YX1 (0.92 ‰). The standard deviations of $\delta^{18}O_{A5}$ (0.38 ‰, n=281) and $\delta^{18}O_{YX1}$ (0.35 ‰, n=77) also have similarity. These results show similar climate change in 3700 years ago and nowadays. The life of *Tridacna* YX1 (11 years) is much shorter than the fossil *Tridacna* (which lived for at least 40 years), thus, modern observation data were used to do the climatic comparison. After translating $\delta^{18}O_{A5}$ into SST (Fig. 5), the reconstructed SST have an average maximum and minimum of 30°C and 25.61 °C, respectively, with seasonal variation of 4.39 °C. Comparatively, the r-monthly average range of modern observation is 29.33 to 23.99 °C (year from 1982 to 2017), with seasonal variation of 5.34 °C. The warmer climate in the past indicates that the seasonality variance is about 0.95 °C lower. Considering the seasonality discrepancy between $\delta^{18}O_{shell}$ and $\delta^{18}O_{predicted}$, the $\delta^{18}O_{shell}$ has 19 % lower seasonal variation than $\delta^{18}O_{predicted}$. Therefore, the actual seasonal variation of A5 (roughly 5.23 °C) is still below the present seasonality.

In addition, the discrepancy between mean $\delta^{18}O_{A5}$ and $\delta^{18}O_{YX1}$ is 0.19 ‰, the lower mean $\delta^{18}O_{A5}$ is because of more r-months in lower values. This reveals a possible prolonged high temperature period: Warm seasons may have been longer, while cold seasons are shorter. From the r-monthly insolation comparison between 3700 years ago (3722 to 3623 BP) and recent decades (1918 to 2017) (Fig. 4d), this coincides with the phenomenon that more insolation occurs from the 2nd to 5th r-month (warm seasons), yet less insolation occurs in the rest of the year. Due to the more samples in *Tridacna* obtained in the warm seasons, the prolonged high temperature period would be magnified (from the 2nd to 6th r-month) (Fig. 4c). Moreover, compared to the deviation between the total average and r-monthly values, cold seasons have larger deviation and slope. This illustrates a fast switching between cold and warm seasons in 3700 years ago. As $\delta^{18}O_{predicted}$ has stronger seasonal variation than $\delta^{18}O_{shell}$, the slope should be sharper, means more significant actual seasonal switching.

Overall, the climate in around 3700 years ago had slightly lower seasonality than present, and the switching between cold to warm seasons was more serious.

4.4 Climate variation comparison between 3700 years ago and present

Global warming is considered to have triggered many disasters (Burgess et al., 2018; Oppenheimer, 2008; Wang et al., 2015; R. Yu et al., 2018). Analogous studies on past warm climate would allow us to better predict the future climate and extreme events if global warming persists. Therefore, we compared modern instrumental observations (year from 1982 to 2017) in the North Reef with the reconstructed SST anomalies of *Tridacna* A5. R-monthly resolution data were first compared, which were obtained by subtracting the r-monthly SST with the mean value of each r-monthly. In terms of long-term climatic variation, the SST anomalies are markedly different between the 36-year modern instrument data and the 40-year reconstructed data (Fig. 6a). The SST anomalies (3700 years ago) have sharper peaks and higher amplitude than in those of the recent years, and the standard deviation in the past is much larger (0.68 °C) than the present (0.42 °C), which suggest a more severe climate condition in the past. However, one has to be aware of the different growth rates and equidistant sampling mode in *Tridacna*'s life when using the r-monthly resolution. For example, *Tridacna* may have different annual growth rates, hence a r-monthly value may not represent the corresponding actual r-monthly value under equidistant sampling mode. In this respect, the r-annual SST anomalies are estimated (Fig. 6b). The SD of modern observation is 0.30 °C, and the SD of reconstructed SST anomalies is 0.41 °C. This illustrates that the ratios of the modern to the past in r-monthly resolution or r-annual resolution are almost the same (0.65 and 0.73, respectively), thus the SD of r-monthly SST anomalies of *Tridacna* is likely reliable. As a result, there was probably an enhanced climate variability 3700 years ago.

4.5 ENSO activity recorded by Tridacna $\delta^{18}O$

ENSO is the strongest signal in global interannual climate variation, and understanding its mechanism is important to unravel the past climate change and forecast in the future one.

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Interannual climate changes in the Xisha Islands were likely dominated by ENSO activity, and the local SST anomalies may have reflected 76.47 % and 79.41 % on moderate El Ninõ and La Niña events, respectively (Liu et al., 2016). Previous studies demonstrated that the marine biogenic carbonate-based SST reconstructions in the northern South China Sea likely responded to ENSO activity (Sun et al., 2005; Yan et al., 2017). Warm/cold SST anomalies were related to El Ninõ/La Niña events. Coral is one of the earliest records for ENSO events (Peng et al., 2003; Sun et al., 2005; Wei et al., 2007), yet there are still some technical limitations, such as those concerning the calcite-affected data (McGregor and Gagan, 2003). Analyses on the *Tridacna* species were later introduced to make up this imperfection, due to their denser shells, negligible diagenetic alteration, and oxygen isotopic equilibrium with seawater. Recently, Yan et al. (2014) proved that *Tridacna* species in the Xisha Islands could respond to ENSO activity, and then used fossil *Tridacna* $\delta^{18}O$ in Dongdao Island (one of the islands in the Xisha Islands) to reconstruct ENSO variability around 2000 years ago (Yan et al., 2017).

To acquire more precise ENSO reconstructions, modern observation data were analyzed. The SST of Ninõ 1 + 2 region was chosen due to the distinct seasonal variation as the same as the study area, and the SST anomaly series were calculated by subtracting the r-monthly mean values (seven points/yr). The spectral analyses were performed to test periodicity among all SST anomalies (Fig. 7), which indicate spectral peak of three to seven years. According to the SST series, the North Reef SST have a 3-month time lag behind the Ninõ 1 + 2 SST (Fig. 8a), and thus we bring 3-month forward to eliminate the lag. To reconstruct the occurrence of ENSO-type in the North Reef, 3-7 years bandpass filtering was performed on the SST anomalies, which yielded a tendency of the North Reef ENSO activity mostly consistent with the Ninõ 1 + 2 SST anomalies (Fig. 8c). We calculated a threshold value under 1σ SST anomalies for moderate El Ninõ/La Niña events. A total of seven El Ninõ and ten La Niña events occurred in the past 36 years. In other words, El Ninõ/La Niña events occurred successively in a 5.14-year frequency in the North Reef.

Spectral analysis revealed that $\delta^{18}O_{A5}$ anomalies also have a 3-7 years period (Fig. 7c). As above discussed, the *Tridacna* $\delta^{18}O$ values are mainly dominated by SST in the Xisha Islands, and 1 ‰ $\delta^{18}O_{shell}$ is roughly equal to 4.41 °C of SST. We translate the $\delta^{18}O_{A5}$ anomalies into the North Reef SST_{A5} anomalies (Fig. 9b). After the 3-7 years bandpass filtering of the North Reef SST_{A5}

anomalies, six El Ninõ and five La Niña events were estimated to occur in 40 years with 1σ SST_{A5} anomalies threshold (Fig. 9c), giving 6.67-year and 8-year frequency, respectively. The ENSO frequency reduces when comparing with the modern observation data. The lower frequency supported the ENSO reconstructions since 7 ka BP, which suggests a notable reduction of ENSO between 5 ka BP and 3 ka BP (Liu et al., 2013; McGregor et al., 2013; Tudhope et al., 2001; Emile-Geay et al., 2016). However, implications drawn from merely 40-year long *Tridacna* $\delta^{18}O$ record is likely inconclusive. Collection of more similar-age *Tridacna* is needed to acquire a more continuous climate and ENSO activity record.

4.6 Extreme winter El Ninõ records in fossil Tridacna $\delta^{18}O$ values

Extreme El Ninõ brings about many climatic disasters, such as catastrophic flooding, bushfire and drought, in recent decades (Ramírez and Briones, 2017; Staupe-Delgado et al., 2018; Yu et al., 2018; Yu et al., 2019). With global warming persists, the question of whether high temperatures are related to extreme El Ninõ events is still controversial. Therefore, records of extreme El Ninõ events in the past warm periods are important. Here, the winter SST is used to estimate the extreme El Ninõ events. Winters in the northern South China Sea are very dry, and the SSS variation caused by rainfall is small. Thus, the SST determined from $\delta^{18}O$ should be close to the actual value. The SST calculated by $\delta^{18}O_{YX1}$ reveal warmer winter in 1998, corresponding to a stronger El Ninõ that year. Comparison between the reconstructed SST (calculated with $\delta^{18}O_{A5}$) and modern observation data from the North Reef (Fig. 5), suggested that the average winter SST in 3700 years ago was 25.62 °C. There are six distinctly high SST within the 40 years, with the anomalies range from 0.73 to 2.00 °C. As for the SST of modern observation (year from 1982 to 2017), the average of winter SST is 23.99 °C, and three anomalously warm temperatures vary from 0.6 to 1.38 °C. It seems that the extreme El Ninõ events occurred under higher temperature and were more frequent in this past warm period. However, we still have low confidence in answering this controversial question about the relationship between El Ninõ events and warm climate, more *Tridacna* in the past warm period should be analyzed in future work. Nevertheless, our results still put forward a high-resolution data that make a contribution to future work on how El Ninõ performs in the warm period.

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5 Conclusions

The $\delta^{18}O$ derived from *Tridacna* provide high-resolution data to unravel the climatic variability and ENSO activity. In the Xisha Islands of northern South China Sea, $\delta^{18}O_{shell}$ of modern *Tridacna gigas* can serve as a proxy of SST, while SSS has a minor effect on $\delta^{18}O_{shell}$. Thus, a $\delta^{18}O$-SST linear regression is established roughly: SST (°C) = 22.69 - 4.41 × $\delta^{18}O_{shell}$. Another *Tridacna squamosa* A5, which lived 3700 years ago, reveals 40 clearly dark/light couples consistent with $\delta^{18}O$ amplitude. Reconstructed SST implies a warmer climate in 3700 years ago, 0.84 °C higher than present. The seasonal variation slightly decreased and the switching among warm and cold seasons was faster. The combination of r-monthly-/r-annual-resolution reconstructed SST anomalies suggest an enhanced climatic variability during this past warm period. Besides, the frequency of ENSO activity reduced in 3700 years ago than that in recent 36-year modern observation. El Ninõ/La Niña events occurred alternatively in every 6.67-/8-year frequency in the past, compared to 5.14-year nowadays. The extreme winter El Ninõ has been recorded by fossil *Tridacna* under an increased and intense situation. Our results imply an unstable climate in 3700 years ago, although more data are still needed to support this hypothesis.

Author Contributions

X. M. S., H. Y., Y. H. designed the research and experiments; H. Y. collected the samples; H. C., Y. H. performed stable isotope measurements. H. Y. and Y. H. did the data analyses. Y. H. wrote the manuscript, with the help of all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Data and materials availability

All data needed to evaluate the conclusions in the paper are presented in the paper. Additional data related to this paper may be requested from the authors. Correspondence and requests for materials should be addressed to X. M. S. (eessxm@mail.sysu.edu.cn) and H. Y. (yanhong@ieecas.cn).

Acknowledgments

This work is supported by the projects from the National 13th Five Year Plan Project (DY135-R2-1-01, DY135-C1-1-06), National Nature Science Foundation of China (41877399,

https://doi.org/10.5194/cp-2019-54
Preprint. Discussion started: 3 June 2019

41876038, 91128101, 41888101), State Key Laboratory for Mineral Deposits Research in Nanjing University (No. 20–15–07), Chinese Academy of Sciences (QYZDB-SSW-DQC001), Qingdao National Laboratory for Marine Science and Technology of China (QNLM2016ORP0202), and. We are grateful to Dr. Yu Fu, Dr. Yang Lu, Dr. Jiaoyang Ruan, Chengcheng Liu, Tianjian Yang, Jun Gu for their support in preparing the manuscript. Dr. Youfeng Ning, Hanying Li, Pengfei Duan, Jingyao Zhao are thanked for their technical support in drilling and analyses in Xi'an Jiaotong University.

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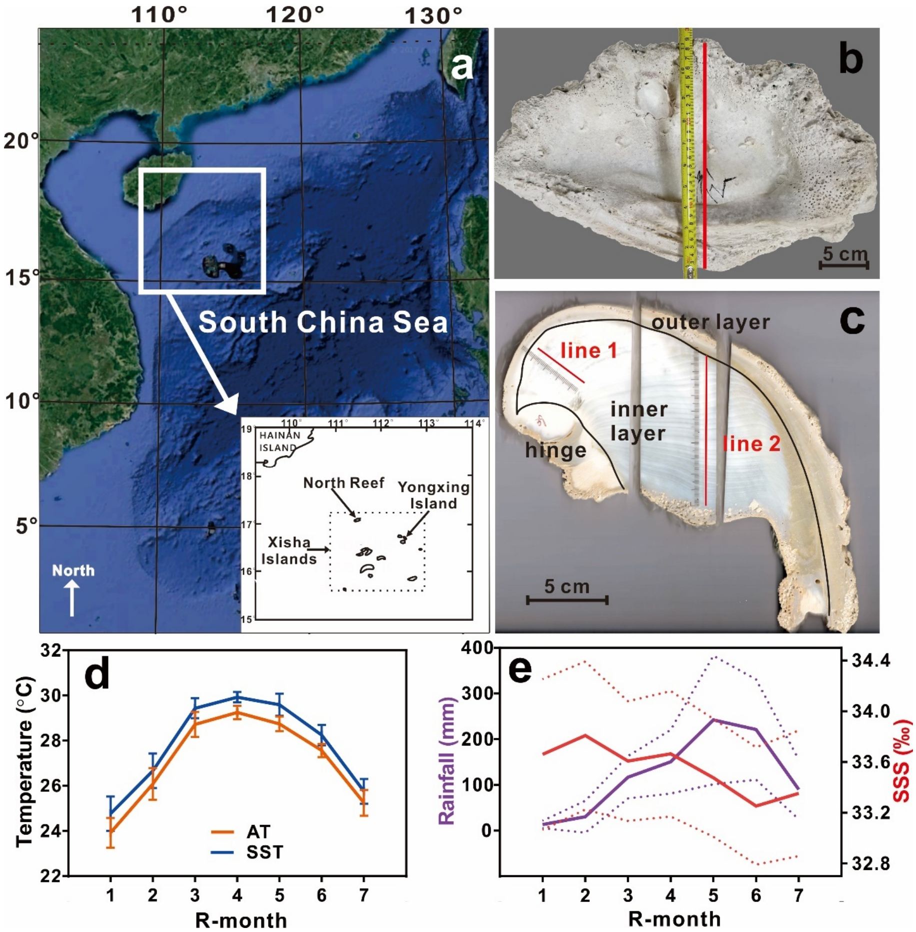
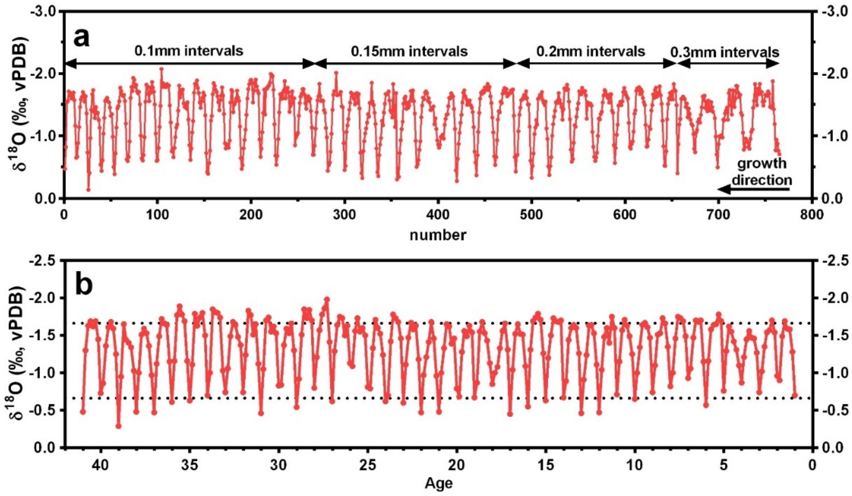
620 **Figures**



621

622 **Figure 1.** Maps of the South China Sea, with the location of the study area in the Xisha Islands (a).
623 Photo of *Tridacna* A5, and a slice was cut along the maximum growth axis (red line) from the
624 umbo to the ventral margin (b). Different parts can be seen clearly (hinge, inner layer, and outer
625 layer) (c), the red lines are the sampling lines for $\delta^{18}O$ analysis. Meteorological observations in the
626 Xisha Islands from 1994 to 2005: R-monthly average air temperature (AT) and sea surface
627 temperature (SST) (d); R-monthly average rainfall and sea surface salinity (SSS) with standard
628 deviation (1σ) (e).



629
630 **Figure 2.** The δ^{18}O profiles of A5 (a). The $\delta^{18}O_{A5}$ series with chronology time-scale after
631 rehandling data, and the dotted lines indicate the average of annual maximum and minimum (b).

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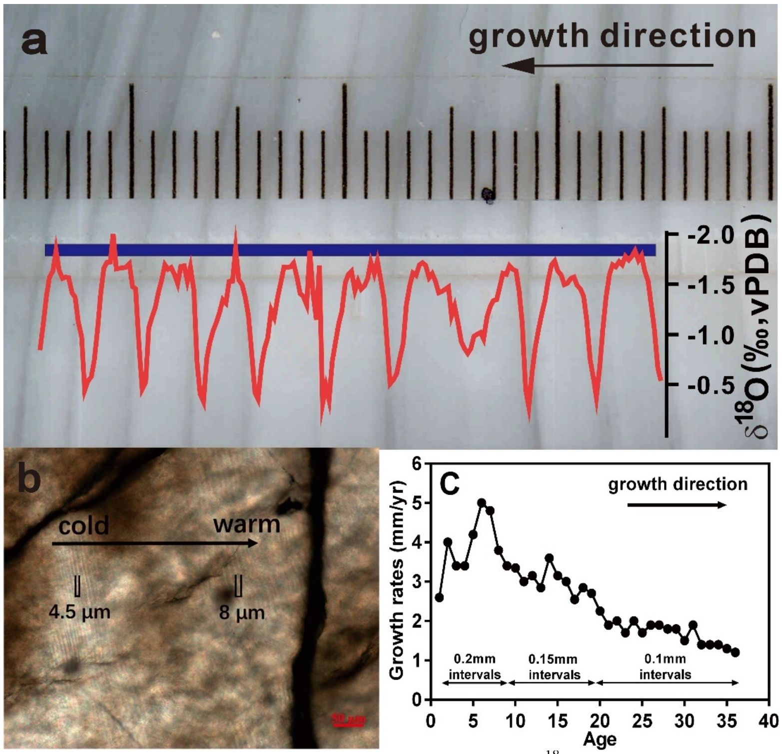

Figure 3. Amplitude of dark/light couples, consistent with $\delta^{18}O_{A5}$ profiles. Dark and light increments correspond to high $\delta^{18}O$ (cold seasons) and low $\delta^{18}O$ (warm seasons). Blue line represents the sampling line (a). Under the microscope, daily increments grow slower in cold seasons, but faster in warm seasons (b). Growth rates (line 2) in fossil *Tridacna* A5 (c).

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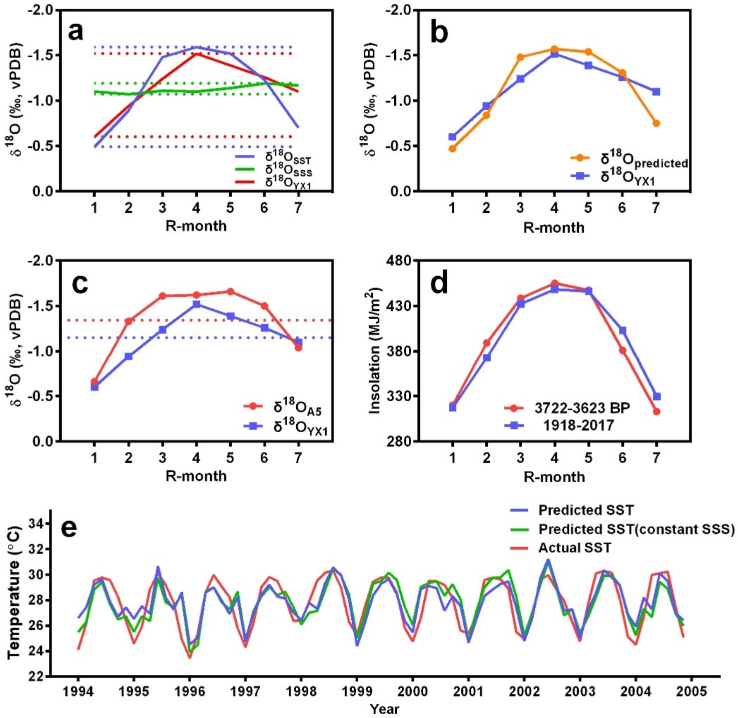

Figure 4. Predicted r-monthly $\delta^{18}O$ profiles under constant SSS (blue line) and constant SST (green line) conditions, and $\delta^{18}O$ of YX1 (red line). Dotted lines represent the maximum and minimum of the r-monthly $\delta^{18}O$ profiles (a). R-Monthly average $\delta^{18}O_{YX1}$ and $\delta^{18}O_{predicted}$ (b). R-monthly average $\delta^{18}O_{YX1}$ and $\delta^{18}O_{A5}$, and the dotted lines represent mean values (c). Different insolation in 3700 years ago and in the recent 100 years (d). Different SST profiles: predicted SST with varied SSS (blue line), constant mean SSS (green line), and actual SST (red line) (e).

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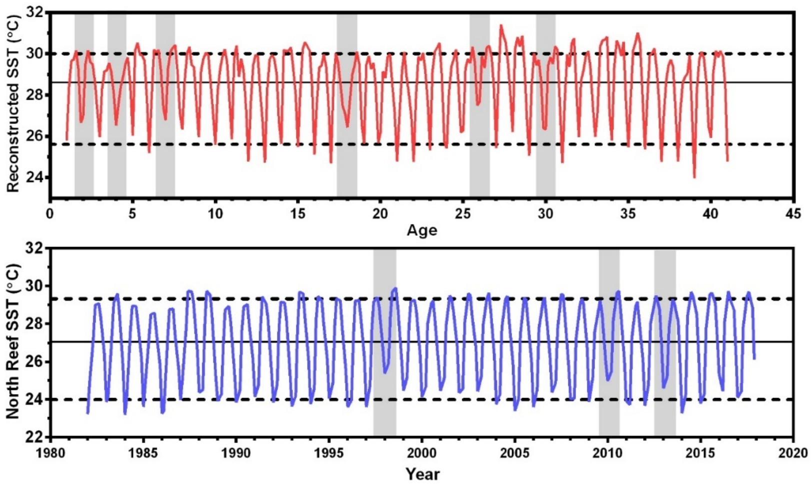

644
645 **Figure 5.** Reconstructed SST around 3700 years ago (red), compared with the North Reef SST
646 from 1982 to 2017 (blue). Dotted lines represent the average maximum and minimum SST. Gray
647 field represents the extreme winter El Ninõ events.

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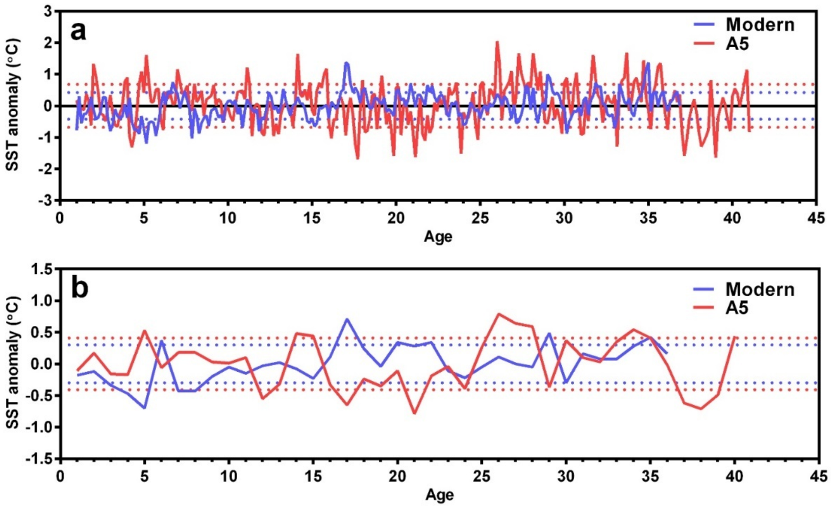

Figure 6. SST anomalies of modern instrument data and reconstructed SST anomalies of *Tridacna* A5 under r-monthly (a) and r-annual (b) resolution. Dotted lines represent one standard deviation (1σ) of SST anomalies.

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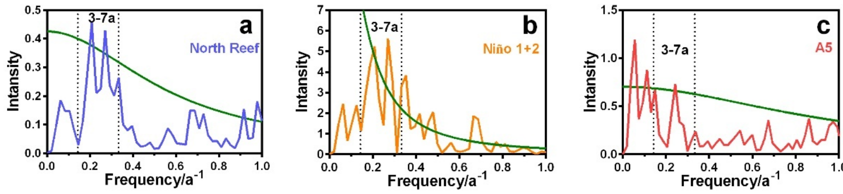

Figure 7. Spectral analysis of the North Reef SST anomalies (a), Ninõ 1 + 2 SST anomalies (b), and reconstructed SST anomalies according to $\delta^{18}O_{A5}$ (c). Green lines indicate significant lines at 90 % confidence level, and the area between two dotted lines represents the frequency from 3 to 7 years.

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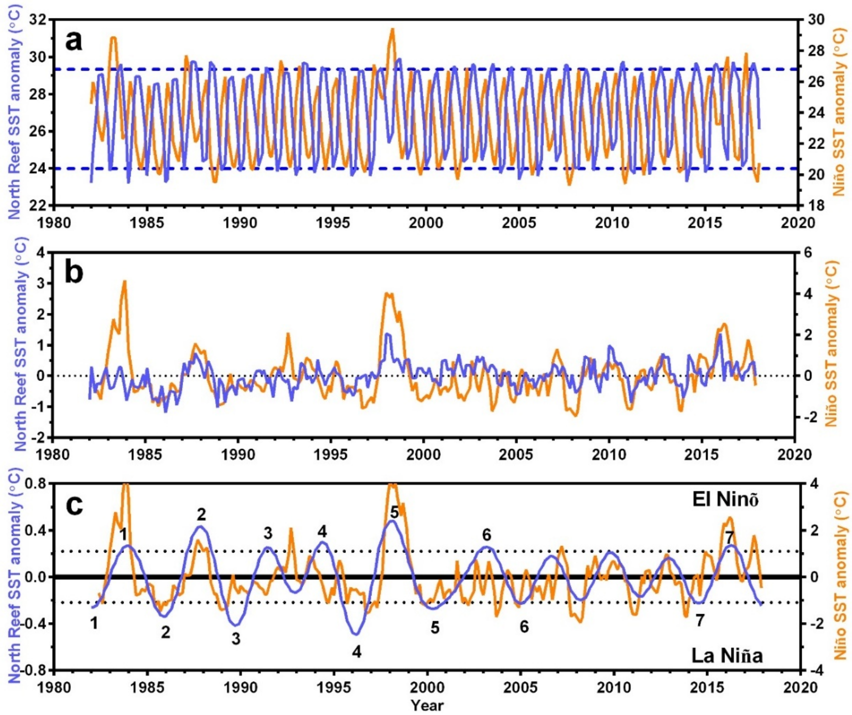

Figure 8. Relationship between ENSO activity and the North Reef SST: The North Reef SST (blue line) compared with Ninõ 1 + 2 SST (yellow line), a clear time lag exists (a). SST anomalies of two areas, and the lag is removed by forwarding the North Reef SST anomalies for 3 r-months (b). The North Reef SST anomalies performed with 3-7 years bandpass filter, consistent with Ninõ 1 + 2 SST anomalies, and the dash lines show the calculated threshold limits (1σ) for El Ninõ and La Niña events in the North Reef (c). El Ninõ and La Niña events are represented by positive and negative SST anomalies values, respectively.

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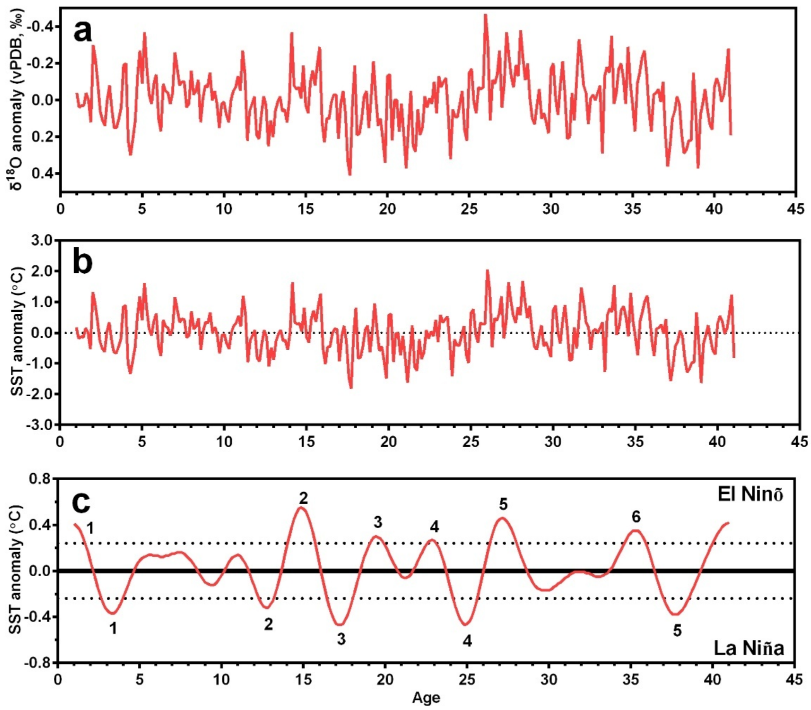

Figure 9. ENSO activity reconstructed by fossil *Tridacna* 3700 years ago: $\delta^{18}O$ anomalies of fossil *Tridacna* A5 (a). The North Reef SST anomalies calculated by $\delta^{18}O$ anomalies (b), based on modern *Tridacna* $\delta^{18}O$-SST equation (1 ‰ $\delta^{18}O_{shell}$ ≈ 4.41°C SST). ENSO activity according to the North Reef SST anomalies after 3-7 years bandpass filtering, and the dash lines show the calculated threshold limits (1σ) for El Ninõ and La Niña events (c).