Interactive comment on "Evidence of intense climate variation and reduced ENSO activity from $\delta^{18}O$ of *Tridacna* 3700 years ago" *by Yue Hu et al.*

Anonymous Reviewer #1:
We would like to thank this reviewer for her/his comments on our manuscript. Please find our detailed answers to each comment below. The reviewer comments are in normal black script, our answers are in blue italics and the revised texts are in blue normal script.

General Comments:

The article presents a new oxygen stable isotope 40-year long record of a 3700 yr BP fossil giant clam Tridacna from the South China Sea. The fossil record is compared to a modern tridacna shell and instrumental data. The authors show clearly that the shells faithfully record SST variations with a nearly monthly resolution. The sclerochronological work is precise and performed with caution. Great attention was given to the effect of sampling resolution. All records were resampled at the same resolution for better comparison of SST ranges and variability. The fossil tridacna shell recorded ENSO variability as shown by the spectral analysis and the 3-7 filtered signal. ENSO signal showed a slightly lower frequency and stronger events at 3700 cal BP compared to the modern reference period. As the author acknowledge, the studied period is too short to draw conclusion on ENSO variability but the study provides high quality new paleoclimate data. Such quantitative seasonally resolved datasets are necessary to achieve a more detailed understanding of the relationship between long-term background changes and seasonal to interannual climate variability.

We thank the reviewer for her/his positive evaluation of our manuscript.

I consider therefore that this is a valuable contribution that needs to be published with minor corrections. The text requires some work with the English. It is generally OK to be read and understood, except for a few sentences that I mention hereafter, but it contains numerous grammatical, syntax and vocabulary errors that need to be fixed. I did not note all the English errors because that is beyond a reviewer's work. In any case, languages issues should not prevent this paper from being published. I hope the journal can assist the authors with language edition.

Thanks for the suggestion, we have checked the errors in our best to improve our manuscript.

Besides this, the introduction and discussion should include a more complete bibliography of paleo-ENSO reconstruction. Key papers such as Koutavas et al. Paleoceanography (2012), Cobb et al. Science (2013), Carré et al., Science (2014) are neither cited nor discussed.

Thank you very much for the classical references. We have added them to our induction and clarified in brief.

A substantial part of the results and discussion is dedicated to changes in the SST seasonality. A new figure showing average seasonal cycles (mean and s.d.) from the fossil, modern, and instrumental record would summarize and clarify greatly the result.

We agree with the reviewer, a figure (Fig. 4e) have added with average seasonal cycles from the data and clarified the result in our manuscript. We only use the data of fossil Tridacna and the modern instrumental record in the figure. This is because they are both in North Reef. Modern Tridacna is located in Yongxing Island (the southern of North Reef), therefore, the seasonality may have deviation which is inappropriate to compare with data in North Reef. To avoid the deviation, we think the average seasonal cycles (minimum, maximum, s.d.) of fossil Tridacna and North Reef instrumental record is better to summarize and clarify the result.

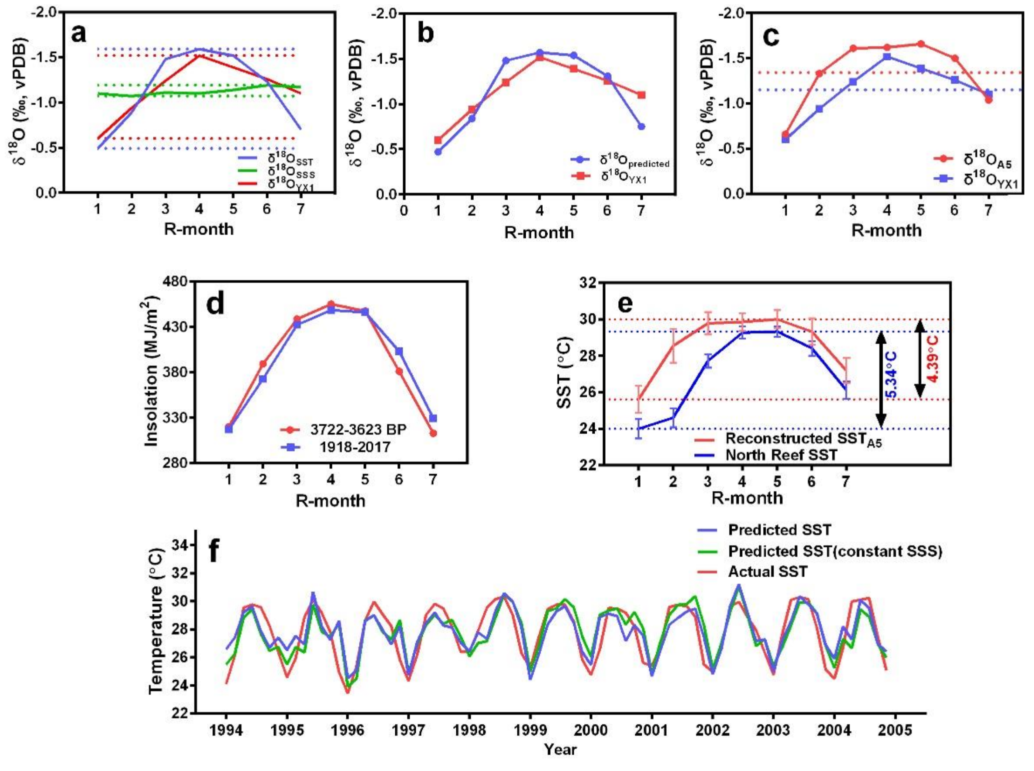

Fig. 4

Detail comments:

L59-60: “ontogenic reduction”: do you refer to the decreasing growth rate with ontogeny?

Yes, as K. Welsh (2011) indicated in his article, the ontogenic reduction in growth of Tridacna gigas does not reduce the reliability with which temperature and $\delta^{18}O_w$ variability can be reconstructed. Climate reconstruction in $\delta^{18}O_{shell}$ does not have an incongruity with temperature and $\delta^{18}O_w$ which might be an obviously declined or increased tendency. We rephrased this sentence to make this clearer:
and the reliability in reconstruction between temperature and seawater $\delta^{18}O$ variability would not be reduced or show obviously declined or increased tendency by the ontogenic growth of the *Tridacna*.

L65: "uncertainties": did you mean "unclear"?

Yes, we have corrected this.

L76: "involved in Holocene Megathermal period", did you mean "part of the Holocene climatic optimum"?

Yes, we have changed the expression to make it clear in the manuscript.

L86: "trigger" should be "source of"

Thank you for your advice. We have corrected this.

L91: Clement et al., 1999 is a modeling study, not a reconstruction.

Thank you. We have corrected it in the text.

L93-98: incomplete bibliography.

Thanks for the suggestion and classical references commends. We have added them to the text and clarified as followed:

Furthermore, the El Ninõ-Southern Oscillation (ENSO) is widely accepted to be the main source of interannual climatic variability in the Pacific Ocean. Previous studies suggested that the 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). Thus, the reconstruction of ENSO is very important for understanding its dynamics and predicting future change. Many early published ENSO behaviors were constructed with low-resolution proxy data using deposition events (Rodbell et al., 1999; Koutavas and Joanides, 2012) and ice cores (Thompson et al., 1995;1998) to reveal the ENSO variance in thousands of years. However, the periodicity of ENSO is short that makes those low-resolution data difficult to demonstrate the strength and variability of ENSO activity precisely. Recent studies focus on seasonal or monthly data to examine the precise variation in ENSO activity

(Arias-Ruiz et al., 2017; Ayling et al., 2015; McGregor et al., 2013; Welsh et al., 2011; Yan et al., 2017), but those fragmental data cannot fully understand the Holocene ENSO dynamics. Therefore, fragments at different times according to different high-resolution samples are needed and can provide an integrated framework for examining ENSO theory and models in Holocene. Besides, studies on the mid to late Holocene ENSO evolution yielded controversial findings: Coral records showed a reduced ENSO variability around the late Holocene (McGregor et al., 2013; Cobb et al., 2013; Woodroffe et al., 2003). Other carbonate species like fossil mollusk shells suggested that ENSO variance was severely damped ~4000 years ago (Carré et al., 2014). Yet some other studies indicated a 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 such as *Tridacna* in unraveling the dynamics of ENSO.

L123-125: "Due to……actual month". This sentence needs to be rewritten. I understood that the records were resampled at 7 data points per year to have comparable time resolution across the records. This number was chosen because it corresponds to the lowest resolution achieved in the fossil record. The verb "rehandle" is used throughout the manuscript but I think "resample" would be more appropriate and clearer. What technique was used for the resampling? Linear interpolation?

Thanks for the suggestion. We agree with you that change the verb "rehandle" into "resample" will be better. The technique we used for the resampling is a cubic spline model in AnalySeries 2.0.8. This method was first applied by Schöne and Fiebig (2009), who used bivalve shells (Arctica islandica) to reconstruct climate. They suggested that 7 points per month would elapse during the core growing season of the shell (i.e., time interval of fastest shell growth covering the seasonal extremes). And only the annual sample number for which equal to or more than seven existed could be used. Therefore, we used 7 points per month. We have added in details in section "2.4 Data processing and analyses".

L144-146: some clarification is needed about the radiocarbon date calibration. What DR value was used? "Conventional" cannot refer to the calibrated date. The calibrated date should not have a +/-28 year uncertainty. Calibration yields a 1sigma or 2 sigma confidence interval and a median date.

From the modern Tridacna samples we collected in this area, the dating results showed no obvious "reservoir effect" (Liu et al., 2019). Tridacna might exchange its carbon with the atmosphere through photosynthesis. Therefore, we used the atmospheric ^{14}C yield model to calibrated. We have clarified the details about the radiocarbon date calibration as followed:

The radiocarbon age determination was performed at Institute of Earth Environment of Chinese Academy of Sciences. The ^{14}C Accelerator Mass Spectrometry data revealed the fossil *Tridacna gigas* age was 3437 ± 28 yr BP. Due to no obvious "reservoir effect" in dating results of modern *Tridacna* shells, the atmospheric ^{14}C yield model was used to calibration. The calibrated date (2σ) was range from 1783 to 1663 cal BC, with the median date is 1741 cal BC by using the IntCal13 of Radiocarbon Calibration Program CALIB 7.10.

L163-167: this part is unclear. Are you comparing values of the internal standards obtained during the analyses of both shells? Is it the same standard material?

The two standard materials are the same material with a different name, we have corrected both of them into "GBW04405" in the text to avoid confusion. This ordovician carbonate is from Zhoukoudian Country, Beijing, China. The certified value and standard deviation had been obtained depend on the comparing with international standard NBS-19, and the result is in ‰ relative to VPDB.

L170-171: "which contained……life span". This is unclear

What we want to express is that the 100 years contain the probable life span of Tridacna when considering the 2 sigma confidence interval of corrected age. We have clarified it clear in the manuscript.

L192: "daily increments are obvious". They are not to me on the figure. Clarify

We have retreated the picture and clarified the details of the daily increments in the text.

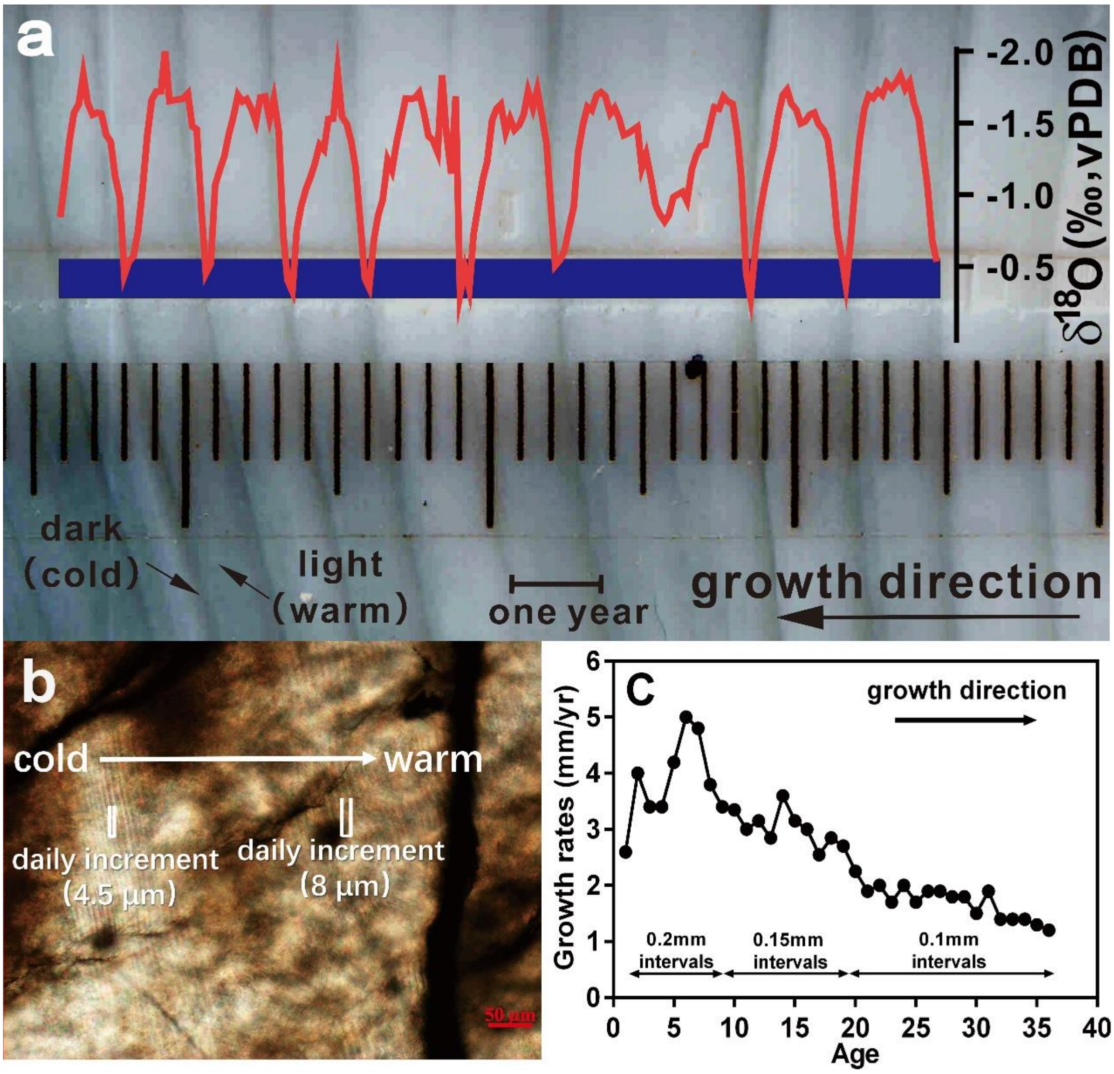

Figure 3. (a) Dark/light lines consistent with $\delta^{18}O_{A5}$ profiles. Dark and light lines correspond to high $\delta^{18}O$ (cold seasons) and low $\delta^{18}O$ (warm seasons), respectively. The distance between the dash lines represents a year that *Tridacna* grew. Blue line represents the sampling line. (b) Under the microscope, daily increments (a dark coupled with a light increment) grow slower when seasons are cold, but faster when temperature rises up. (c) Growth rates (line 2 in Fig. 1c) in fossil *Tridacna* A5.

L226: "perfect match, r=0.81". perfect sounds too strong. Why is $\delta^{18}O_{YX1}$ better correlate to $\delta^{18}O_{SST}$ (r=0.91) than to $\delta^{18}O_{predicted}$ (r=0.81) if this latter includes both SST and SSS and should therefore be more realistic?

Thank you for your advice, we have rewrote this phrase.
$\delta^{18}O_{SST}$ were calculated in actual varied SST and constant SSS, $\delta^{18}O_{predicted}$ were calculated in both actual varied SST and SSS. Theoretically speaking, $\delta^{18}O_{YX1}$ should have a better correlation to $\delta^{18}O_{predicted}$. But our results are not. These might due to the significant control on SST to $\delta^{18}O_{shell}$. $\delta^{18}O_{SSS}$ are nearly negative correlated with $\delta^{18}O_{SST}$. This might reduce the correlation when using both actual varied SST and SSS to calculate.

L214 – L240: these paragraphs could be shorter and clearer if the information was better organized and presented.

We have rewrote these paragraphs into:

The $\delta^{18}O_{shell}$ reflect a combination of SST and SSS variation. In order to quantify more precisely the relation between those factors and $\delta^{18}O_{shell}$, two $\delta^{18}O$ profiles are calculated: $\delta^{18}O_{SST}$ (constant SSS but varying SST) and $\delta^{18}O_{SSS}$ (constant SST but varying SSS) (Fig. 4a). R-monthly mean values are used to compare for they are minimizing the influence of extreme events. The results show $\delta^{18}O_{YX1}$, $\delta^{18}O_{SST}$, and $\delta^{18}O_{SSS}$ profiles are range from -0.57 to -1.52 ‰, -0.48 to -1.58 ‰, -1.07 to -1.19 ‰, respectively. It is obviously that $\delta^{18}O_{YX1}$ and $\delta^{18}O_{SST}$ have same trend and high correlation ($r = 0.91$, $n = 7$; $r = 0.78$, $n = 77$), but the variation range in $\delta^{18}O_{SSS}$ is only 14 % of $\delta^{18}O_{YX1}$. Therefore, this indicates $\delta^{18}O_{shell}$ in the Xisha Islands correspond predominantly to the seasonal SST variation. Besides, the calculated $\delta^{18}O_{predicted}$ (by using both local 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 their positive correlation ($r = 0.81$, $n = 77$) indicates the local *Tridacna* precipitates its shell in oxygen isotopic equilibrium.

Moreover, the comparison of predicted SST (under constant SSS and actual SSS with $\delta^{18}O_{YX1}$) further confirms that the SSS variation have no significant affection in local reconstructed SST (Fig. 4f). Two predicted SST values have high similarity ($r = 0.93$), and they are well correlated with the actual SST ($r_{vary} = 0.79$, $r_{constant} = 0.78$). Thus, we can 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) = $22.69 - 4.41 \times \delta^{18}O_{shell}$ (or $\delta^{18}O_{shell}$ (‰) $= -0.136 \times \mathrm{SST} + 2.634$). A 1 ‰ change of $\delta^{18}O_{shell}$ is roughly equal to 4.41°C of SST. Yu (2005) summarized many published $\delta^{18}O$-SST slopes for the other marine carbonate species, *Porites lutea* coral, and suggested that the slopes could range from -0.134 to -0.189. Corals from Hainan Island revealed a good $\delta^{18}O$ vs. SST correlation with a linear regression slope of -0.137 (Su et al., 2006), very similar to our result (-0.136). Consequently, it is reliable to use the new linear regression for reconstructing the past SST with the fossil $\delta^{18}O_{shell}$.

L244: “variance”. Do you refer to the seasonal range?

We have rephrased this sentence in the text to clarify:

The difference in seasonality between $\delta^{18}O_{YX1}$ and $\delta^{18}O_{predicted}$ is 0.18 ‰, which is accounts for 19 % of $\delta^{18}O_{YX1}$.

L244: 0.19% check this number.

Thank you. The number should be 19 %. We have corrected it in the text.

L277: “indicates” do you mean “associated with”?

Yes, we have corrected this.

L269-280: The total range of the signal includes not only seasonality but also interannual to decadal variability. To evaluate the change in the seasonal range, it would be more appropriate to estimate and compare the mean seasonal ranges.

Thank you for your advice, we have added this figure in Fig. 4e (see above).

L288: “Moreover……slope” this is unclear

We have rewrote the sentence:
Moreover, comparing from each r-monthly value to average value, cold seasons have a larger deviation with greater slope.

L290-292: a figure of mean seasonal cycles would be useful

We have added this figure in Fig. 4e.

L296-299: these short introductions about global warming are not necessary

Thanks for your suggestion, we have removed these sentences.

L320: unclear

We have rewrote this sentence to:
The local accumulated positive percentage of monthly SST anomalies threshold could respond to 76.47 % El Ninõ and 79.41 % La Niña events in Ninõ 3.4 region (Liu et al., 2016).

L333: unclear

We have rewrote those sentences to:
To acquire more precise ENSO reconstructions, modern observation data were analyzed and compared with the SST in Ninõ 1 + 2 region. The SST anomaly series were calculated by subtracting the r-monthly mean values.

Reference

Schöne, B. R. and Fiebig, J.: Seasonality in the North Sea during the Allerød and Late Medieval Climate Optimum using bivalve sclerochronology, Int. J. Earth Sci., 98(1), 83–98, doi:10.1007/s00531-008-0363-7, 2009.

Welsh, K., Elliot, M., Tudhope, A., Ayling, B. and Chappell, J.: Giant bivalves (*Tridacna gigas*) as recorders of ENSO variability, Earth Planet. Sci. Lett., 307(3–

4), 266–270, doi:10.1016/j.epsl.2011.05.032, 2011.
Liu, C., Yan, H., Fei, H., Ma, X., Zhang, W. and Shi, G.: Journal of Asian Earth Sciences Temperature seasonality and ENSO variability in the northern South China Sea during the Medieval Climate Anomaly interval derived from the Sr / Ca ratios of *Tridacna* shell, J. Asian Earth Sci., 180(June), 1-9, doi:10.1016/j.jseaes.2019.103880, 2019.

Anonymous Reviewer #2:
We would like to thank this reviewer for her/his careful reading on our manuscript. Please find our detailed answers to each comment below. The reviewer comments are in normal black script, our answers are in blue italics and the revised texts are in blue normal script.

General Comments:

Hu et al. present a new oxygen stable isotope record of a fossil giant clam from the South China Sea, which reveals new high resolution insights into the ENSO activity dated back 3700 yr BP and fine-tuned using a modern Tridacna for comparison. As this study fits well into the journal's scope I rate this manuscript to be of high interest to the audience of Climate of the Past and encourage publication after minor revision. As the study was carried out on only one specimen it has a "case study-like" read, however, the authors convince me that their application bears high potential for a potential larger-scale study with more specimens. The manuscript is well structured and outlined. The methodological part appears sound, which is apparent when e.g. sampling resolutions are discussed. I feel the introduction could benefit from discussing and citing more sclerochronological papers discussing oxygen stable isotope records from bivalves (they don't have to relate to the sampling site) and I would strongly argue that a recent paper demonstrating shell architecture of Tridacna ought to be mentioned and cited (Agbaje et al.2017). Further, I have some comments to the title (see below) and there are a few other (mostly language) issues that I feel need fixing before moving forwards and I provide a list of more detailed comments below to address these. I enjoyed reading this study and hope the authors will find my suggestions helpful and encouraging!

We thank the reviewer for his/her positive evaluation of our manuscript, and the detailed comments he/she suggested are really helpful. We have checked those errors to improve our manuscript and answered the questions in detail below.

Specific comments:

L1-2: I believe the use of "ENSO" in the title is not wise. Titles should be fully understandable to a broad audience and community-specific abbreviations should be avoided. I'd urge the authors to type out "ENSO" or phrase this differently. Also it may be good to use "Giant Clam" instead of "Tridacna" in the title.

Thank you for your suggestion, we have corrected them.

L22: “are the largest marine bivalves” and “carbonaceous shell” and “can be used for high-resolution paleoclimate reconstructions”.

Done.

L47: delete “of”.

Done.

L48: “physicochemical” is weird in this context – do you want to record environmental signatures encoded within the biocarbonate or do you want to look at physiological variations that may or may not be influences by external factors?

We have rewrote this expression. Here, we refer to both environmental records by biochemistry ($\delta^{18}O$) and ontogenetic change (e.g. daily increment with dark/light couples) in Tridacna. “physicochemical” has been replaced by “biochemical and ontogenetic”.

L49: “on past climate dynamics” delete “the”.

Done.

L50-51: I recommend also citing the most recent work on the crossed-lamellar shell architecture of Tridacna see reference: Agbaje, O. B. A., R. Wirth, L. F. G. Morales, K. Shirai, M. Kosnik, T. Watanabe, and D. E. Jacob. "Architecture of crossed-lamellar bivalve shells: the southern giant clam (Tridacna derasa, Röding, 1798)." Royal Society open science 4, no. 9 (2017): 170622.

Done.

L54: I doubt that Tridacna lives up to “few centuries” where is the evidence (reference)? This may have been mixed up with Arctica shells or other long-lived bivalves but these are very different from Tridacna!

We apologies for having made a mistake in the text and have changed the expression to “from several decades to about a hundred year”*. Some people in China said they had found an about 200 years old Tridacna gigas, but it has not been confirmed by authorities. From the Tridacna gigas we collected, the oldest one had lived about 100 years, most of them are between 30 to 60 years.*

L57: “precipitate” is really a wrong term when talking about shells as it is closely associated with classical crystallisation pathways (i.e. “inorganic” systems). However, we know for more than over a decade now that shells form by non-classical crystallization pathways via precursor phases (amorphous calcium carbonate and/or vaterite). I am not saying you need to venture into the area of shell biomineralization here but I would strongly argue to find a better word for this text passage. Maybe replacing “precipitate their shells” with simply “grow”.

We accept the referee’s suggestion, and have replaced the word “precipitate” into “grow”.

L59-60: What do you mean with “ontogenetic reduction”?

“ontogenic reduction” refers to the decreasing growth rate with ontogeny. This word was mentioned by K. Welsh (2011). As K. Welsh indicated in his article, the ontogenic reduction in growth of T. gigas does not reduce the reliability with which temperature and $\delta^{18}O_w$ variability can be reconstructed. Climate reconstruction in $\delta^{18}O_{shell}$ don’t have an incongruity with temperature and $\delta^{18}O_w$ which might be an obviously declined or increased tendency. We have rephrased this sentence to make this clearer:
and the reliability in reconstruction between temperature and seawater $\delta^{18}O$ variability would not be reduced by the ontogenic growth of the *Tridacna*.

L80: “occurring nowadays”, however, I think you should try and find a more appropriate word than “nowadays” as this sounds perhaps too casual and please replace throughout manuscript.

As suggested by the reviewer, we have replaced the word “nowadays” into “recent decades” or “present”.

L83-84: Better: “High-resolution isotopic geochemical data from Tridacna may provide detailed insight into climatic variations of this period.”

Done.

L117: “give distinct seasonal SST to the Tridacna from the coral reefs” reads clumsy, perhaps change to “provide distinct seasonal SST for Tridacna populating the coral reefs of the Xisha Islands”.

Done

L123-125: I don’t understand “rehandling” do you mean “re-sampling”? I agree with referee 1 that this sentence needs to be rewritten for more clarity. Please change throughout the manuscript.

Thanks for the suggestion. We agree with you that change the verb “rehandle” into *"resample" will be better. The technique we used for the resampling is a cubic spline model in AnalySeries 2.0.8. This method was first applied by Schöne and Fiebig (2009), who used bivalve shells (Arctica islandica) to reconstruct climate. They suggested that 7 points per month would elapse during the core growing season of the shell (i.e., time interval of fastest shell growth covering the seasonal extremes). And only the annual sample number for which equal to or more than seven existed could be used. Therefore, we used 7 points per month.*

L130-131: Perhaps better: "It is excluded that river runoff effects SSS as the Xisha Islands are at a XXX km distance to the continental mainland." Please quantify roughly to provide evidence.

Done.

L138-143: I recommend providing a sentence regarding the crossed-lamellar shell architecture of Tridacna see above mentioned reference Agbaje et al. (2017).

We thank the referee for his/her advice and have added them in the manuscript as follow:
Study in shell architecture showed a crossed lamellar microstructure with a strong fibre texture made the mechanical properties of those bivalve shells more optimized (Agbaje et al., 2017).

L144: when you mention "^{14}C AMS" for the first time I recommend providing the full method name in brackets (replace "^{14}C AMS" with "^{14}C AMS (Accelerator Mass Spectrometry)") for readers that lack this methodological background.

Done.

L145: I don't understand the meaning of "conventional" in this sentence – maybe not the right phrase? What is the uncertainty? First or second standard deviation or something else?

From the modern Tridacna samples we collected in this area, the dating results showed no obvious "reservoir effect" (Liu et al., 2019). Tridacna might exchange its carbon with the atmosphere through photosynthesis. Therefore, we used the atmospheric ^{14}C yield model to calibrated. We have clarified the details about the radiocarbon date calibration as followed:
The radiocarbon age determination was performed at Institute of Earth Environment of Chinese Academy of Sciences. The ^{14}C Accelerator Mass Spectrometry data revealed the fossil *Tridacna gigas* age was 3437 ± 28 yr BP. Due to no obvious "reservoir effect" in dating results of modern *Tridacna* shells, the atmospheric ^{14}C yield model was used to calibration. The calibrated date (2σ) was range from 1783 to 1663 cal BC, with the median date is 1741 cal BC by using the IntCal13 of Radiocarbon Calibration Program

CALIB 7.10.

L154: “from adult to childhood” is not the right phrase how about “in a transect from adult to ontogenetically younger shell”?

Thank you for your advice, we have replaced this phrase.

L185: “40 dark/light couples (each representing one year)” please explain how dark/light line couples relate to time/tide schedules/seasonality. How much time/which tide pattern does one dark-light line couple stand for?

We have added them to clarify as follow:

From the shell slice section, dark/light line couples (each couple represents one year) can be seen clearly (Fig. 3a). Follow the $\delta^{18}O_{A5}$ profiles, those short and dark lines (transparent) corresponding to higher $\delta^{18}O_{A5}$ values, which means *Tridacna* grew in low temperature (cold seasons such as December to February). In contrast, lower $\delta^{18}O_{A5}$ values lie in the long and light lines (opaque), corresponding to the high temperatures (warm seasons such as March to November).

L192: Increments are not obvious to me from the image. Especially Fig. 3b is not clear what one should see, perhaps choose a different image with better resolution.

It’s really hard to take a clear picture from Tridacna A5 for the organic matter influence. Those organic matter covered most of increments and make those increments unclear. We had tried our best to find this picture under microscope with obvious increments change. We have retreated the picture contrast and brightness to make them clear as the reviewer’s suggestion.

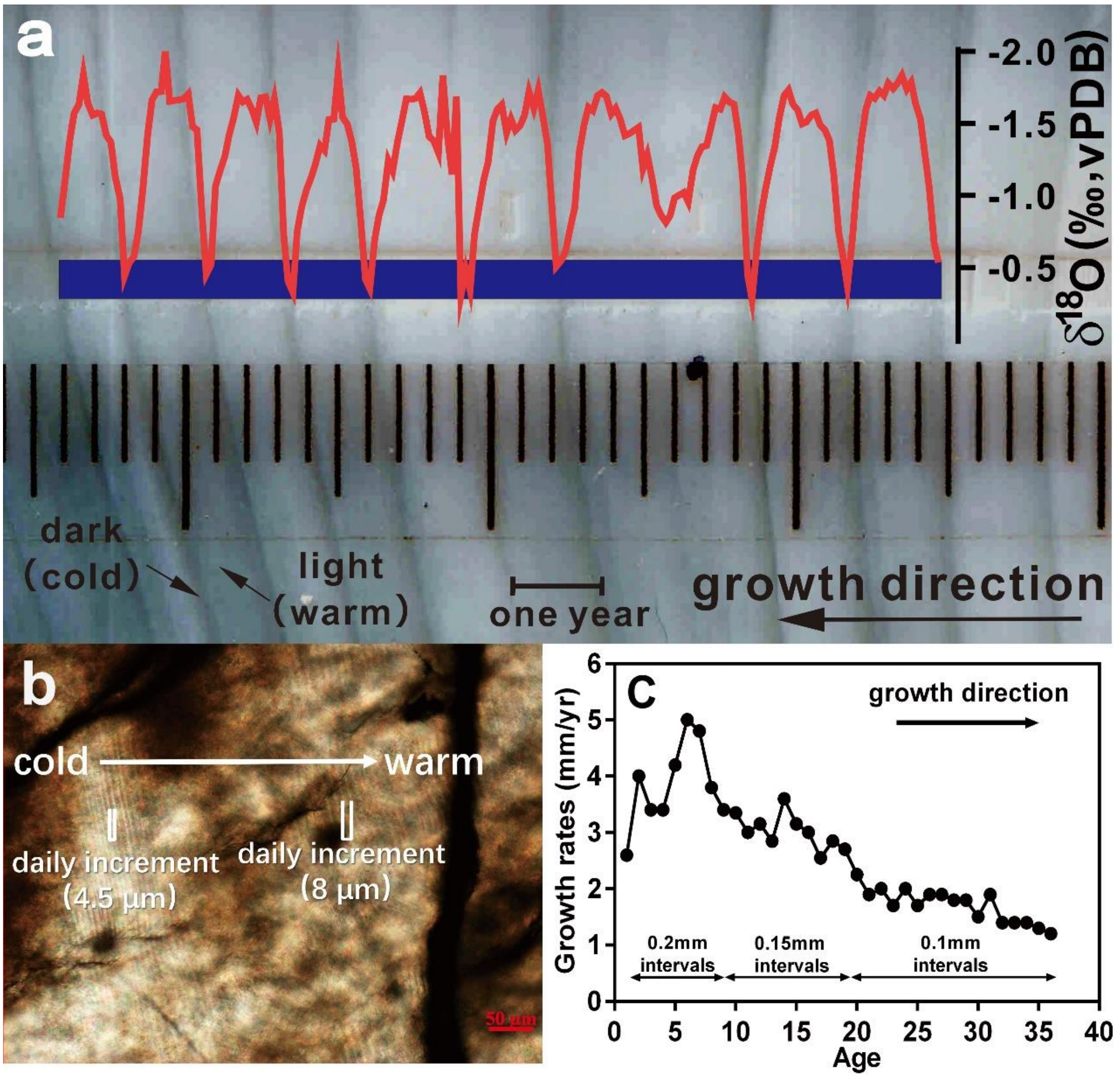

Figure 3. (a) Dark/light lines consistent with $\delta^{18}O_{A5}$ profiles. Blue line represents the sampling line. Dark and light lines correspond to high $\delta^{18}O$ (cold seasons) and low $\delta^{18}O$ (warm seasons), respectively. The distance between the dash lines represents a year that *Tridacna* grew. (b) Under the microscope, daily increments (a dark coupled with a light increment) grow slower when temperature is cold, but faster when the temperature rises up. (c) Growth rates (line 2 in Fig. 1c) in fossil *Tridacna* A5.

L192-193: "In general, Tridacna A5 grew faster in warm seasons and slower in cold seasons (Fig. 3b)." Where is your evidence for this assumption? I feel you need to back this up as this varies between species and you need to demonstrate to the reader that it is the case for Tridacna. Also, more seasonal information may be needed to achieve this. How long are summers how long are winters? For example: if a reader believes summer and winter are similar in length one could misinterpret short low $\delta^{18}O$ periods may have just been formed quicker (and have thus higher not lower growth rates!). This all needs more explanation and demonstration and is important as you build upon this later in the discussion. Perhaps see other papers I suggest any study by Carré et al as they are very educative in this respect.

This evidence focuses on Fig. 3b and we added more clarification in section 2.4. As we mentioned above, it's hard to see entirely increments in a year because of the organic matter influence. However, some fragments near the highest $\delta^{18}O_{shell}$ (indicating this period happened in cold season) show the increments change as the $\delta^{18}O_{shell}$ become lower (temperature become higher). From Fig. 3b, the daily increment is about 2.7 μm in low temperature, while as the temperature rises up, the daily increment can reach to 5.7 μm. It happened normally throughout Tridacna's life. Therefore, we have this conclusion that Tridacna grew faster in warm seasons and slower in cold seasons. Meteorological observations reveal that the cold seasons happened from about December to February, the rest of months are relatively suitable for Tridacna to grow fast. But it's hard to distinguish exactly how long is cold and how long is warm through Tridacna's increments. The growth rates influence on $\delta^{18}O_{shell}$ cannot be eliminated. However, we use the resampling method suggested by Schöne and Fiebig (2009), which try to reduce this problem as much as possible.

L196-197: I don't understand this sentence.

As suggested by Schöne and Fiebig (2009), the technique we used for the resampling that would elapse during the core growing season of shell (i.e., time interval of fastest shell growth covering the seasonal extremes). Also, before we resample the data, the numbers of annual data change because of different growth rates. To some extent, data resampling makes annual data become comparable. We have removed this sentence, for it is improper to explain here. The resampling method have added in details in section 2.4 in our manuscript.

L201: Perhaps not everything about Tridacna but $\delta^{18}O$?

You are right, we have changed this phrase into "oxygen isotopic equilibrium".

L259: "lived 3700 years ago" delete "in".

Done.

L286-287: Better: "Due to a higher sampling density in Tridacna: : :".

Done.

L288: "magnified" is the wrong word here.

Thank you. We have replaced the word into "enlarged".

L292: "switching" wrong word, replace throughout manuscript.

Thank you. We have replaced the word into "transition".

L293-294: This sentence contradicts itself and needs rewording for clarity.

The seasonality is the range between the lowest temperature and the highest temperature in the text. In order to eliminate the different influence in location, we use the reconstructed SST_{A5} and North Reef SST (from NOAA) to compare and the result shows the seasonality in 3700 years ago had slightly lower. Besides, the transition between cold to warm seasons focuses on the slope of $\delta^{18}O_{shell}$ when temperature change from low to high (or high to low), mainly focus on 1st r-month to 2nd r-month (or 6th r-month to 7th r-month). This situation is better to compare between two $\delta^{18}O_{shell}$ (modern and fossil) because the monthly data are not equal to evenly instrumental data. Therefore, we can see in Fig. 4c, the slope of A5 is obviously sharper than YX1, which means the transition between cold to warm seasons was more serious 3700 years ago. In conclusion, we consider that the climate around 3700 years ago had slightly lower seasonality than present, and the transition between cold to warm seasons was more serious.

L296-299: reads more like an introduction section and is not relevant here (suggest to delete).

As suggested by both two reviewers, we have removed this section.

L303: “instrumentation data” is odd.

Thank you. We have replaced the word into “modern instrumental data”.

L326: “calcite-affected” sounds also a bit odd to me maybe you can find a better term. Why is calcite “bad” in this sense? Why is it a limitation?

*We apologize for this confusion in the text. We have replaced this sentence into “*such as those concerning the post-depositional diagenetic alteration between aragonite and calcite*”. As McGregor and Gagan (2003) indicated in their research, some corals had both aragonite and calcite in their skeleton, the range between them in $\delta^{18}O$ could reach to nearly 3‰. Such alteration should be paid more attention before we use for accurate paleoclimate reconstructions.*

L326-328: Better perhaps: “Analyses of Tridacna species are performed to overcome this limitation by taking advantage of their denser shells, negligible diagenetic alteration, and oxygen isotopic equilibrium with seawater.”

Done.

L338: unclear.

Do you mean that there is an unclear about which one we bring 3-month forward? We added this for clarification:

According to the SST series, the North Reef SST have a 3-months time lag behind the Ninõ 1 + 2 SST (Fig. 8a), and thus 3-month of the North Reef SST are brought forward to eliminate the lag.

Figure 1: It looks like your 5 cm scale bar is too large for the scale in the figure (measuring tape, here 5 cm look smaller). There are some grammar issues in the figure caption.

We apologize for having made this mistake in the scale bar and have replaced the right one. Figure caption had rewritten as follow:

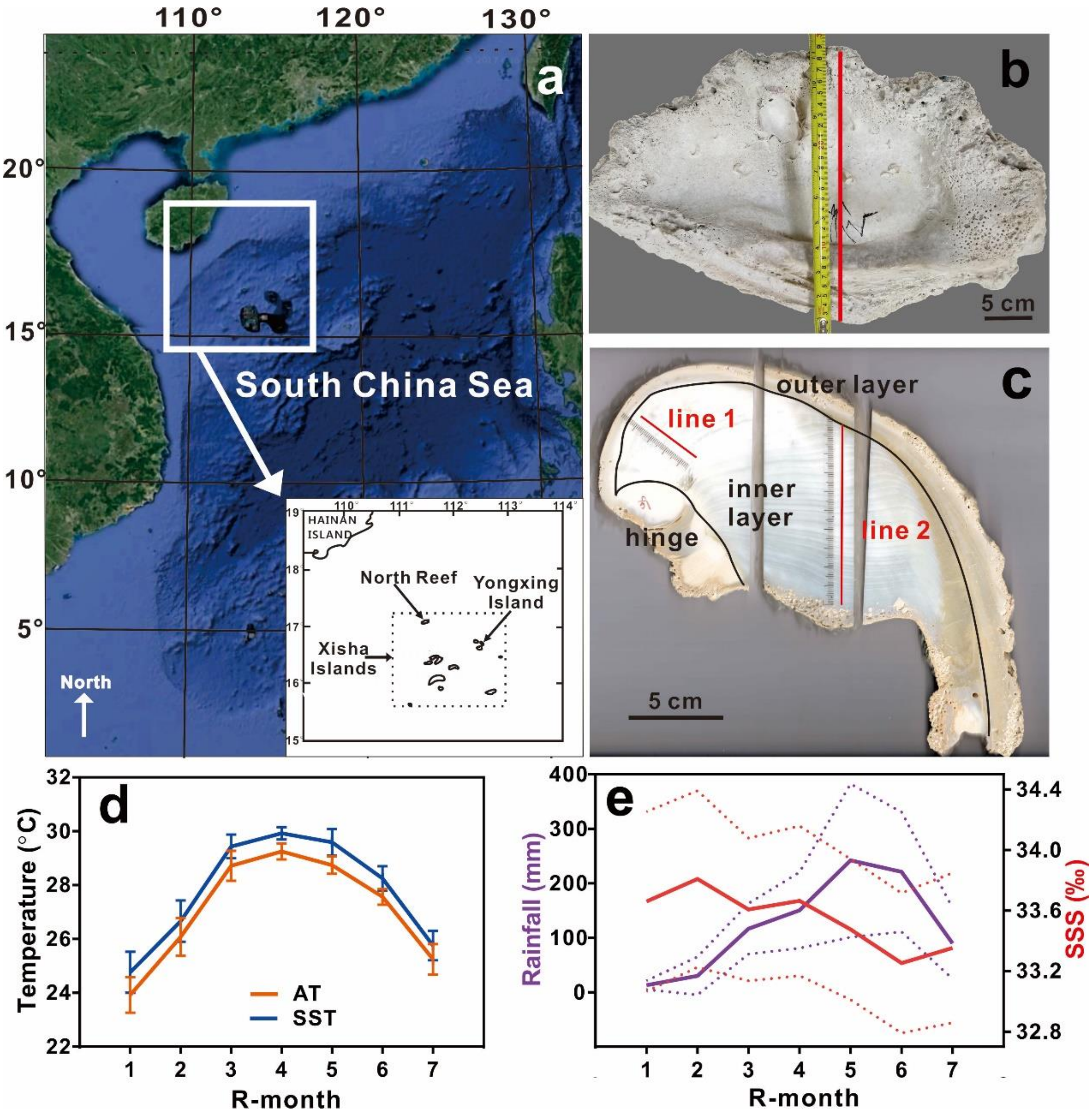

Figure 1. (a) Maps of the South China Sea, with the location of the sample study area in the Xisha Islands. (b) Photo of integral *Tridacna* A5, a slice was cut from the red line of integral *Tridacna* A5. (c) Different parts can be seen (hinge, inner layer, and outer layer), the red lines are the sampling lines for $\delta^{18}O$ analysis. (d) Meteorological

observations in the Xisha Islands from 1994 to 2005: r-monthly average air temperature (AT) and sea surface temperature (SST), the error bars reveal the highest and the lowest temperature in the month; (e) R-monthly average rainfall and sea surface salinity (SSS) with standard deviation (1σ).

L633: “amplitude” may not be the right word here.

We have removed this word and rewrote this sentence.

L635-636: “under the microscope, daily increments grow slower in cold seasons, but faster in warm seasons” – this is not visible from microscope images alone! This needs more explanation! Also, image is not really easy to understand (what should be seen? It’s all very blurry).

As suggested by the reviewer, we have replaced the photo of Fig. 3b and added for more clarification in the 2nd paragraph of section 3.2:

Furthermore, daily increments (a dark coupled with a light increment) can be seen under the microscope (Fig. 3b). A fragment was chosen where $\delta^{18}O$ were near highest in a year. This period lied on the cold season which daily increment was about 2.7 μm. When the temperature rose up as warm season began, *Tridacna* grew faster that daily increment could reach to 5.7 μm. This situation occurred throughout *Tridacna*’s life. In general, *Tridacna* A5 grew faster in warm seasons and slower in cold seasons.

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Evidence of intense climate variation and reduced El Nino-Southern Oscillation activity from $\delta^{18}O$ of Giant Clam 3700 years ago

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Abstract

Giant clams (*Tridacna*) are the largest marine bivalves in the tropical ocean, and their carbonate shells can be used for 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 resampled monthly (r-monthly) resolution of *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 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 modern instrumental data, and the transition 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.

Keywords: *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 high-resolution biochemical and ontogenetic variations in their skeleton, these marine biogenic carbonates can shed light on past climate dynamics. Bivalves, which are considered to be high-resolution records, can give us more precisely environmental variation details. Studies in bivalve mollusk specimen (*Arctica islandica*) oxygen isotopes showed a different seasonal temperature change compared between the Little Ice Age and the present (Schöne et al., 2005; Wanamaker et al., 2011). Giant clam (*Tridacna)*, 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; Agbaje et al., 2017). This is because 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 longevity from several decades to about one hundred years. 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 grow their shells with the oxygen 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 reliability in reconstruction between temperature and seawater $\delta^{18}O$ variability would not be reduced or show obviously declined or increased tendency by the ontogenic growth of the *Tridacna* (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 influences on $\delta^{18}O_{shell}$ are unclear due to the distinct variation of temperature and salinity in different areas. 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 one part of the Holocene Megathermal period (8 to 3 ka BP). Sediments in the South China Sea also implied the temperature might relatively higher in the early of Meghalayan than the 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 happened in recent decades, 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 from *Tridacna* may provide detailed insight into the climatic variations of this period.

Furthermore, the El Ninõ-Southern Oscillation (ENSO) is widely accepted to be the main source of interannual climatic variability in the Pacific Ocean. Previous studies suggested that the 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). Thus, the reconstruction of ENSO is very important for understanding its dynamics and predicting future change. Many early published ENSO behaviors were constructed with low-resolution proxy data using deposition events (Rodbell et al., 1999; Koutavas and Joanides, 2012) or ice cores (Thompson et al., 1995;1998) to reveal the ENSO variance in thousands of years. However, the periodicity of ENSO is short that makes those low-resolution data difficult to demonstrate the strength and variability of ENSO activity precisely. Recent studies focus on seasonal or monthly data to examine the precise variation in ENSO activity (Arias-Ruiz et al., 2017; Ayling et al., 2015; McGregor et al., 2013; Welsh et al., 2011; Yan et al., 2017), but those fragmental data cannot fully understand the Holocene ENSO dynamics. Therefore, fragments at different times according to different high-resolution samples are needed and can provide an integrated framework for examining ENSO theory and models in Holocene. Besides, studies on the mid to late Holocene ENSO evolution yielded controversial findings: Coral records showed a reduced ENSO variability around the late Holocene (McGregor et al., 2013; Cobb et al., 2013; Woodroffe et al., 2003). Other carbonate species like fossil mollusk shells suggested that ENSO variance was severely damped ~4000 years ago (Carré et al., 2014). Yet some other studies indicated a 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 such as *Tridacna* in unraveling the dynamics of ENSO.

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 is substantially influenced by two contrasting Asian monsoons from opposite directions: The Asian summer monsoon from the southwest and the Asian winter monsoon from the northeast. These two monsoons provide distinct seasonal SST for Tridacna populating 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. 1b).

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 suggested in the method (Schöne and Fiebig, 2009) and the yearly minimum number of $\delta^{18}O_{YX1}$ was seven, the time-scale of modern *Tridacna* YX1 is resampling into seven points/yr, which indicates a resampled month (r-month) represents 1.7 actual month. All meteorological observations and $\delta^{18}O_{shell}$ are using this method to resample 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 are about 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. It is excluded that river runoff effects SSS as the Xisha Islands are about 300 km away from the continental mainland (Hainan Island). 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 fossil *Tridacna* has three different zones (Fig. 1c): the inner layer, outer layer and the hinge. Study in shell architecture showed a crossed lamellar microstructure with a strong fibre texture made the mechanical properties of those bivalve shells more optimized (Agbaje et al., 2017). 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 ontogeny (Welsh et al., 2011), and could better reflect actual $\delta^{18}O$ than the outer layer or the hinge (Pätzold et al., 1991; Elliot et al., 2009).

The radiocarbon age determination was performed at Institute of Earth Environment of Chinese Academy of Sciences. The ^{14}C Accelerator Mass Spectrometry data revealed the fossil *Tridacna gigas* age was 3437 ± 28 yr BP. Due to no obvious "reservoir effect" in dating results of modern *Tridacna* shells, the atmospheric ^{14}C yield model was used to calibration (Liu et al., 2019). The calibrated date (2σ) was range from 1783 to 1663 cal BC, with the median date is 1741 cal BC by using the IntCal13 of 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

Each stable isotope sample was micromilled parallel 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 in a transect from adult to ontogenetically younger shell (Fig. 2a).

$\delta^{18}O$ 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 standard GBW04405, which had been compared with international standard NBS-19, were added to the analyses every 10 to 20 samples to check the reproducibility. The average value of standard powder in $\delta^{18}O$ is -8.49 ± 0.14 ‰. Duplicate measurements of GBW04405 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, 90 km ESE of the North Reef (Fig. 1b). Internal carbonate standard of modern *Tridacna* YX1 $\delta^{18}O$ (VPDB) was also GBW04405, the standards and samples had reproducibility (1σ) of better than 0.08 ‰ and 0.06 ‰, respectively.

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 probable life span of *Tridacna* (A5) when considering the two sigma confidence interval of corrected age. The time-scale of modern insolation range from 1918 to 2017, while *Tridacna* A5 range from 3722 to 3623 BP. Statistical analyses were performed with software Origin 2018 and PAST 3.18. Due to the different growth rates influence on $\delta^{18}O_{shell}$ cannot be eliminated, and organic matter influence on counting whole increments, a resampling method was used to reduce this problem. Since suggested in the method and the yearly minimum number of $\delta^{18}O_{YX1}$ was seven, thus the isotopic records, climatic data and insolation data were resampled to seven points/yr with the AnalySeries 2.0.8 (Schöne and Fiebig, 2009; Wanamaker et al., 2011). This resampling method could reduce the influence of growth rates in one year, for 7 points per month would elapse during the core growing season of the shell (i.e., time interval of fastest shell growth covering the seasonal extremes) (Schöne and Fiebig, 2009).

3 Results

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

Seasonal cycles are distinct in the $\delta^{18}O_{A5}$ profile (Fig. 2), which indicate this *Tridacna* had lived for 40 years. The $\delta^{18}O_{A5}$ range from -2.07 to -0.14 ‰ (mean -1.35 ‰, n=765). After resampling 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, dark/light line couples (each couple represents one year) can be seen clearly (Fig. 3a). Follow the $\delta^{18}O_{A5}$ profiles, those short and dark lines (transparent) corresponding to higher $\delta^{18}O_{A5}$ values, which means *Tridacna* grew in low temperature (cold seasons such as December to February). In contrast, lower $\delta^{18}O_{A5}$ values lie in the long light lines (opaque), corresponding to the high temperatures (warm seasons such as March to November). Annual growth rates can be calculated with the $\delta^{18}O_{A5}$ seasonal cycles and interval distance (Fig. 3c). 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 (Fig. 3c). Furthermore, daily increments (a dark coupled with a light increment) can be seen under the microscope (Fig. 3b). A fragment was chosen where $\delta^{18}O$ were near highest in a year. This period lied on the cold season which daily increment was about 2.7 μm. When the temperature rose up as warm season began, *Tridacna* grew faster that daily increment could reach to 5.7 μm. This situation occurred throughout *Tridacna*'s life. In general, *Tridacna* A5 grew faster in warm seasons and slower in cold seasons.

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.

4 Discussion

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

Previous studies demonstrated that *Tridacna* is in oxygen isotopic equilibrium with the surrounding seawater (Aharon, 1983; Watanabe et al., 1999), which also holds true for the *Tridacna* in the 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). The $\delta^{18}O_{shell}$-SST-$\delta^{18}O_{water}$ Eq. (1) of Grossman and Ku (1986) was adopted for its widely used in calculations for tropical aragonite mollusk species. Meanwhile, $\delta^{18}O_{water}$ have a positive relationship to SSS, and Eq (2) which is established through seawater in the northern South China Sea (Hong et al., 1997) was chosen to calculate. We merge Eq (1) and (2) into $\delta^{18}O_{shell}$-SST-SSS (Eq (3)) to roughly simplify the environmental control on $\delta^{18}O_{shell}$.

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

$\delta^{18}O_{water}$ (‰) = 0.23 × SSS – 7.58 (2)

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

The $\delta^{18}O_{shell}$ reflect a combination of SST and SSS variation. In order to quantify more precisely the relation between those factors and $\delta^{18}O_{shell}$, two $\delta^{18}O$ profiles are calculated: $\delta^{18}O_{SST}$ (constant SSS but varying SST) and $\delta^{18}O_{SSS}$ (constant SST but varying SSS) (Fig. 4a). R-monthly mean values are used to compare for they are minimizing the influence of extreme events. The results show $\delta^{18}O_{YX1}$, $\delta^{18}O_{SST}$, and $\delta^{18}O_{SSS}$ profiles are range from -0.57 to -1.52 ‰, -0.48 to -1.58 ‰, -1.07 to -1.19 ‰, respectively. It is obviously that $\delta^{18}O_{YX1}$ and $\delta^{18}O_{SST}$ have same trend and high correlation ($r = 0.91$, $n = 7$; $r = 0.78$, $n = 77$), but the variation range in $\delta^{18}O_{SSS}$ is only 14 % of $\delta^{18}O_{YX1}$. Therefore, this indicates $\delta^{18}O_{shell}$ in the Xisha Islands correspond predominantly to the seasonal SST variation. Besides, the calculated $\delta^{18}O_{predicted}$ (by using both local 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 their positive correlation ($r = 0.81$, $n = 77$) indicates the local *Tridacna* precipitates its shell in oxygen isotopic equilibrium.

Moreover, the comparison of predicted SST (under constant SSS and actual SSS with $\delta^{18}O_{YX1}$) further confirms that the SSS variation have no significant affection in local reconstructed SST (Fig. 4f). Two predicted SST values have high similarity ($r = 0.93$), and they are well correlated with the actual SST ($r_{vary} = 0.79$, $r_{constant} = 0.78$). Thus, we can 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 many published $\delta^{18}O$-SST slopes for the other marine carbonate species, Porites lutea coral, and suggested that the slopes could range from -0.134 to -0.189. Corals from Hainan Island revealed a good $\delta^{18}O$ vs. SST correlation with a linear regression slope of -0.137 (Su et al., 2006), very similar to our result (-0.136). 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

According to $\delta^{18}O_{YX1}$ (-0.60 to -1.52 ‰) and $\delta^{18}O_{predicted}$ (-0.47 to -1.57 ‰) profiles (Fig. 4b), seasonality is shown with the lowest value occurring in the 1st r-month (cold season) and the highest value in the 4th r-month (warm season). The difference in seasonality between $\delta^{18}O_{YX1}$ and

$\delta^{18}O_{predicted}$ is 0.18 ‰, which is accounts for 19 % of $\delta^{18}O_{YX1}$. This situation 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 $\delta^{18}O_{shell}$ yearly amplitude is more approached to the actual $\delta^{18}O_{predicted}$ under more number of points (fast growth rate) before it reached maturity. After the *Tridacna* reach maturity, the fewer points obtained under equidistance mode 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 $\delta^{18}O_{YX1}$ (-1.15 ‰) and mean $\delta^{18}O_{predicted}$ (-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 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 r-monthly average profiles, the extreme seasonal variation effects were minimized. The mean $\delta^{18}O_{A5}$ 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 that *Tridacna* A5 lived in a warmer season. To translate into SST (without considering the SSS changes), the temperature was estimated to be roughly 0.84°C higher than the present. This agrees with other lines of evidence that suggested a higher temperature during that period (Ouyang et al., 2016), and that period 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 SD of $\delta^{18}O_{A5}$ (0.38 ‰, n=281) and $\delta^{18}O_{YX1}$ (0.35 ‰, n=77) also have a similarity. These results show similar climate change in 3700 years ago and in present. However, the life of *Tridacna* YX1 (11 years) is much shorter than the fossil *Tridacna* (which lived for at least

40 years), and YX1's location is in the southern of A5, thus modern observation data in North Reef 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 (Fig. 4e). 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 (Fig. 4e). The warmer climate in the past associated with the seasonality variance is about 0.95 °C lower. Considering the seasonality discrepancy between $\delta^{18}O_{shell}$ and $\delta^{18}O_{predicted}$ that 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 mean $\delta^{18}O_{YX1}$ 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 in 3700 years ago: warm seasons may have been longer, while cold seasons are shorter. This coincident with a comparison between 3700 years ago (3722 to 3623 BP) and recent decades (1918 to 2017), which indicates *Tridacna* A5 lived in more insolation which occurs from the 2nd to 5th r-month (warm seasons), yet less insolation occurs in the rest of the months (Fig. 4d). Thus, the prolonged high-temperature in the past might attribute to more insolation. Besides, although a higher sampling density obtained in the warm seasons enlarges the high-temperature period (from the 2nd to 6th r-month), cold to warm transition could still be recognized from A5 and YX1 $\delta^{18}O$ profiles (Fig. 4c). Comparison from each r-monthly value to average value shows r-month between 1st to 2nd have a larger deviation with a greater slope in 3700 years ago. This illustrates a fast transition 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, which means more significant actual seasonal transition.

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

4.4 Climate variation comparison between 3700 years ago and present

A comparison was performed between the modern instrumental observations (year from 1982 to 2017) in the North Reef and 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 instrumental 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 SD 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, the deviation should be awared when there are different growth rates in *Tridacna*'s life and equidistant sampling mode. 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 to reduce the deviation (Fig. 6b). The SD of modern observation SST anomalies 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. Interannual climate changes in the Xisha Islands were likely dominated by ENSO activity. The local accumulated positive percentage of monthly SST anomalies threshold could respond to 76.47 % El Ninõ and 79.41 % La Niña events in Ninõ 3.4 region (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 reveals 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 post-depositional diagenetic alteration between aragonite and calcite (McGregor and Gagan, 2003). Analyses of *Tridacna* species are performed to overcome this limitation by taking advantage of their denser shells, no 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 and compared with the SST in Ninõ 1 + 2 region. The SST anomaly series were calculated by subtracting the r-monthly mean values. 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-r-months time lag behind the Ninõ 1 + 2 SST (Fig. 8a), and thus 3-r-months of the North Reef SST were brought 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 that the North Reef ENSO activity mostly consistent with the Ninõ 1 + 2 SST anomalies (Fig. 8c). A threshold value was calculated 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. $\delta^{18}O_{A5}$ anomalies were transformed 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. A collection of more similar-age *Tridacna* is needed to acquire a more continuous climate and ENSO activity record in Holocene.

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 $\delta^{18}O_{shell}$ 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. A 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 (gray fields in Fig. 5), 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 0.60 to 1.38 °C. It seems that the extreme El Ninõ events were much frequent in this past warm period. However, it still has 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 events perform in the warm period.

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 in 3700 years ago, reveals 40 clearly dark/light line couples consistent with $\delta^{18}O_{shell}$ profiles. Reconstructed SST implies a warmer climate in 3700 years ago, 0.84 °C higher than the present. The seasonal variation slightly decreased and the transition among cold to warm seasons was faster. The combinations 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 in recent decades. The extreme winter El Ninõ has been recorded by fossil *Tridacna* with 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).

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Figures

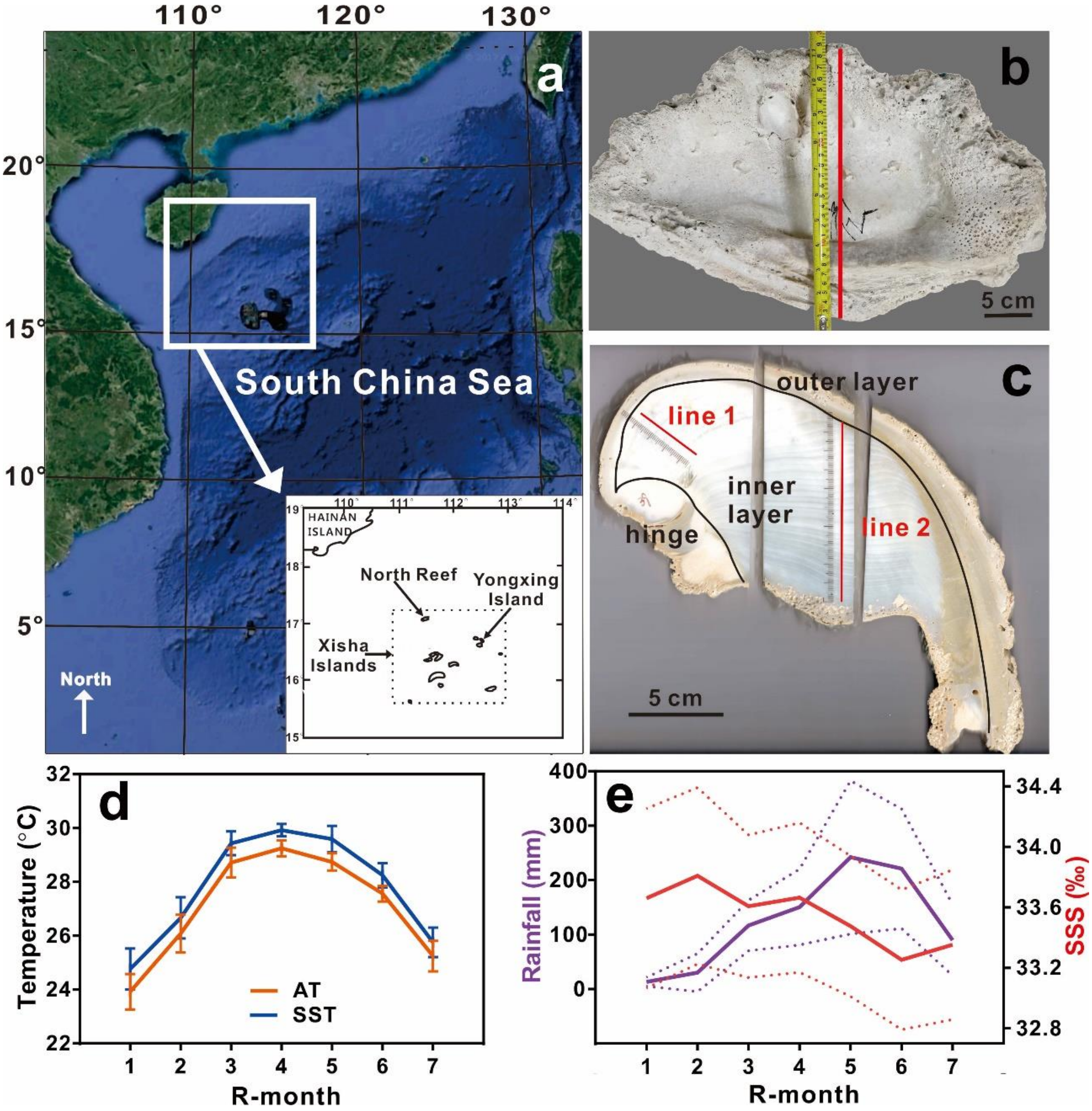

Figure 1. (a) Maps of the South China Sea, with the location of the sample study area in the Xisha Islands. (b) Photo of integral *Tridacna* A5. A slice was cut through the red line of integral *Tridacna* A5. (c) Different parts can be seen (hinge, inner layer, and outer layer), the red lines are the sampling lines for $\delta^{18}O$ analysis. (d) Meteorological observations in the Xisha Islands from 1994 to 2005: r-monthly average air temperature (AT) and sea surface temperature (SST), the error bars reveal the highest and the lowest temperature in the month; (e) R-monthly average rainfall and sea surface salinity (SSS) with standard deviation (1σ).

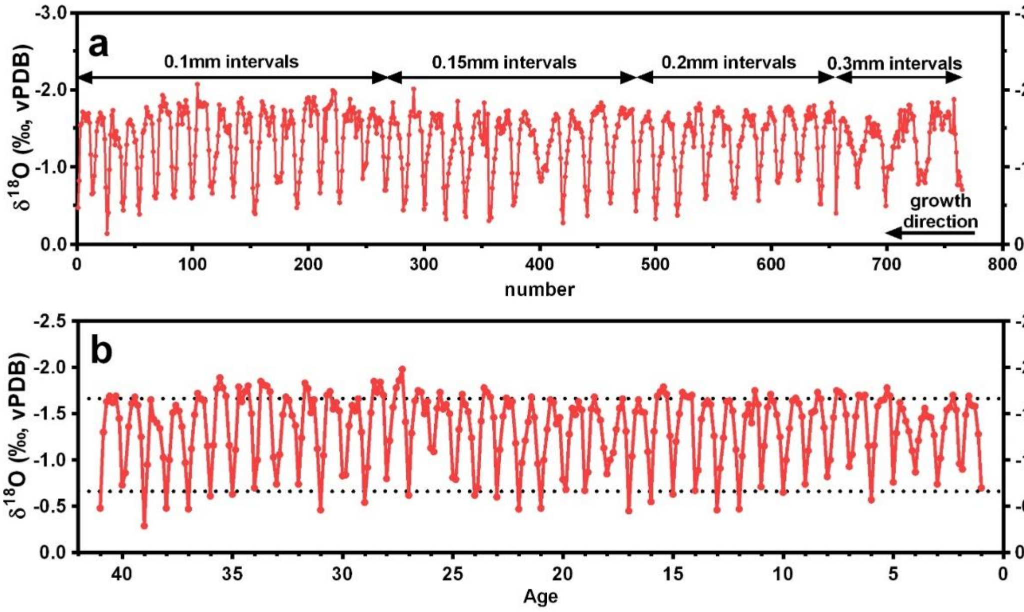

Figure 2. (a) The $\delta^{18}O$ profiles of A5. (b) The $\delta^{18}O_{A5}$ profiles with chronology time-scale after resampling data, and the dotted lines indicate the average of annual maximum and minimum.

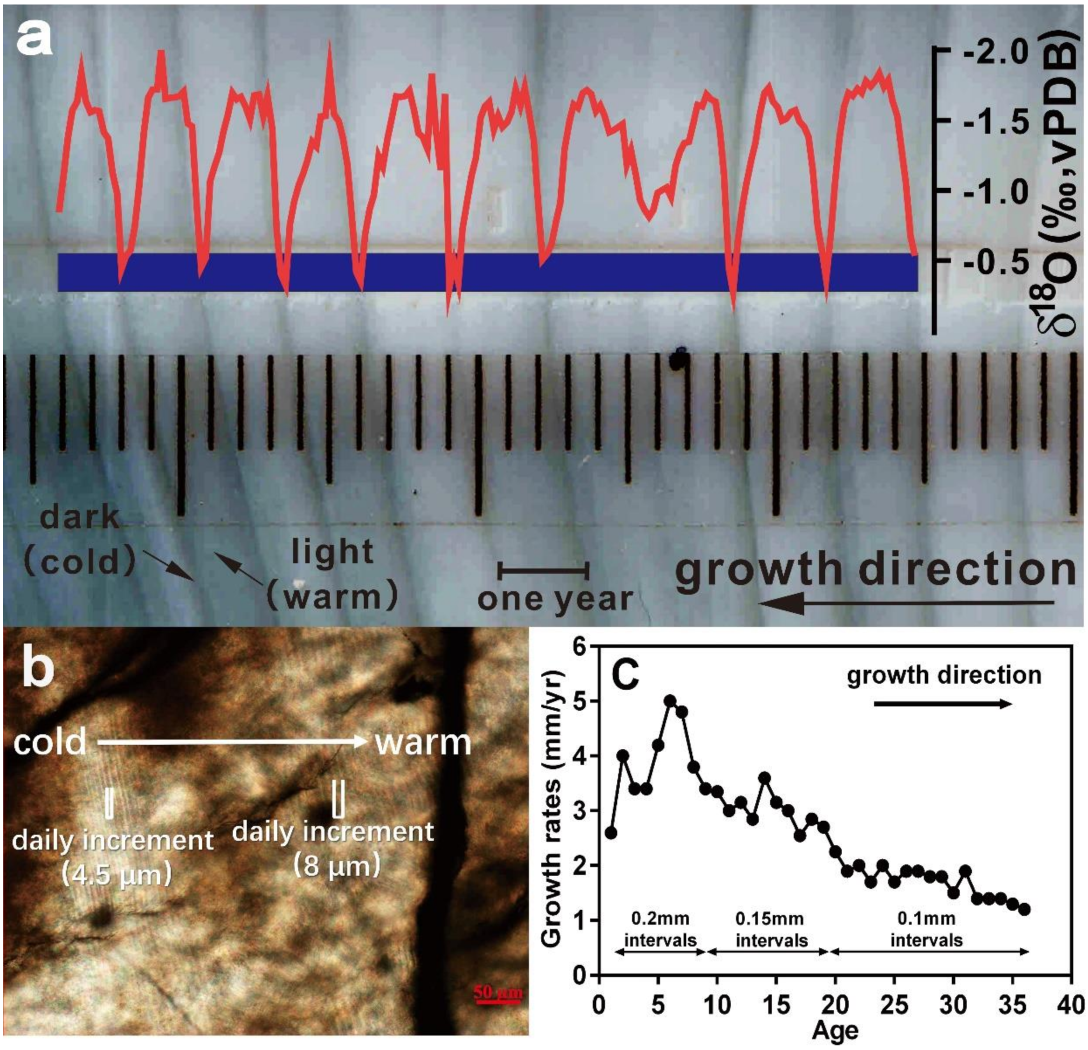

Figure 3. (a) Dark/light lines consistent with $\delta^{18}O_{A5}$ profiles. Blue line represents the sampling line. Dark and light lines correspond to high $\delta^{18}O$ (cold seasons) and low $\delta^{18}O$ (warm seasons), respectively. The distance between the dash lines represents a year that *Tridacna* grew. (b) Under the microscope, daily increments (a dark coupled with a light increment) grow slower when temperature is cold, but faster when temperature rises up. (c) Growth rates (line 2 in Fig. 1c) in fossil *Tridacna* A5.

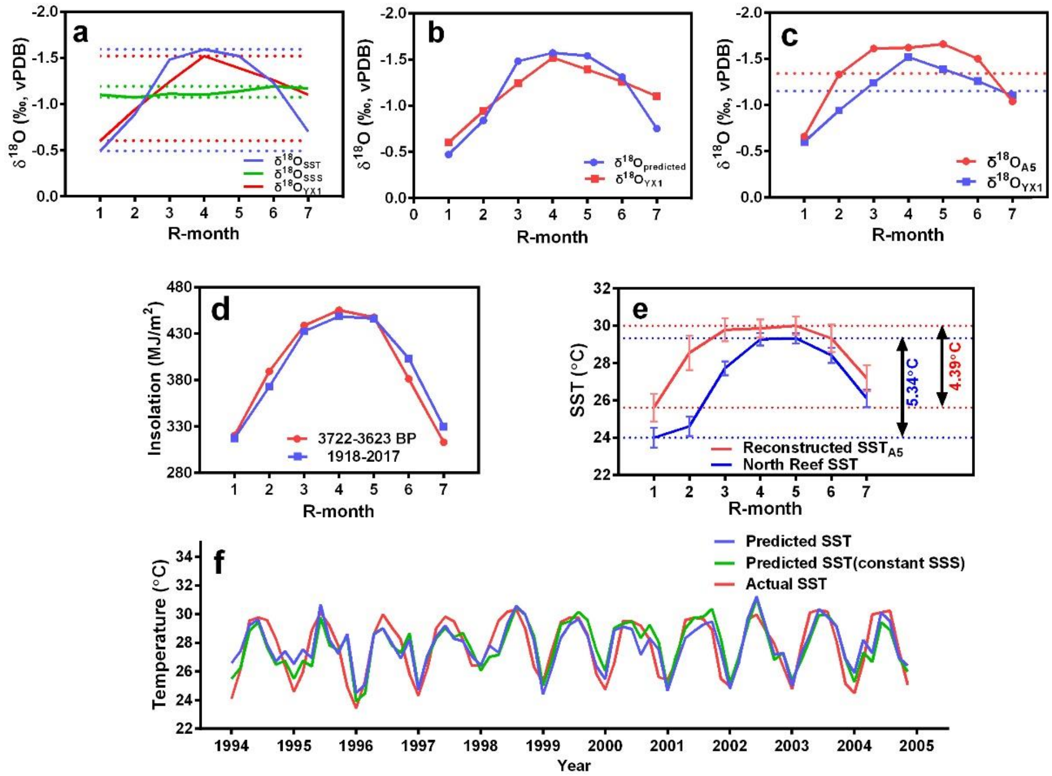

Figure 4. (a) Predicted r-monthly $\delta^{18}O$ profiles under constant SSS (blue line) and constant SST (green line) conditions, and $\delta^{18}O$ of YX1 (red line). Dotted lines represent the maximum and minimum of the r-monthly $\delta^{18}O$ profiles. (b) R-monthly $\delta^{18}O_{YX1}$ and $\delta^{18}O_{predicted}$.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

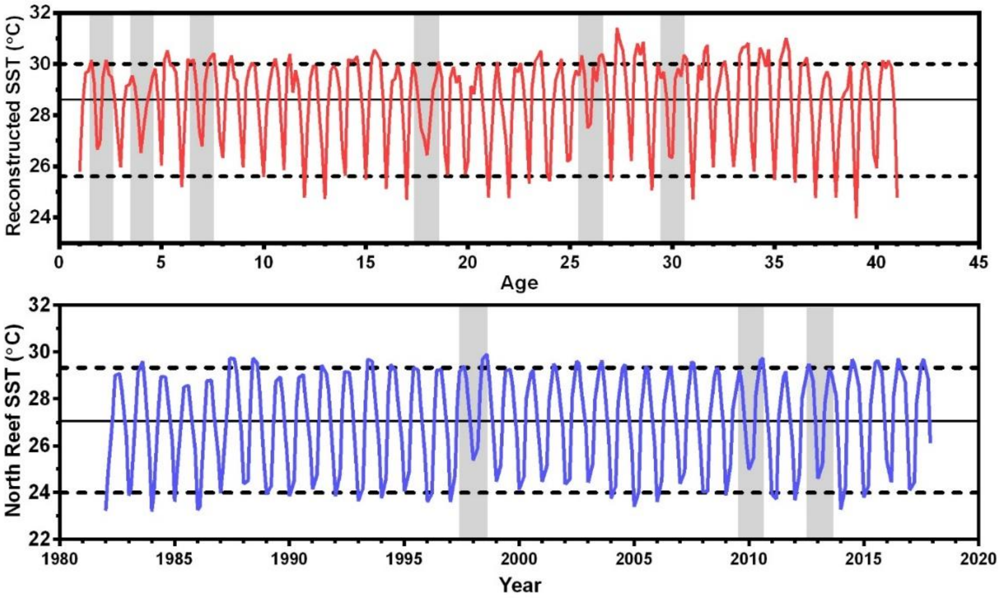

Figure 5. Reconstructed SST around 3700 years ago (red), compared with the North Reef SST from 1982 to 2017 (blue). Dotted lines represent the average maximum and minimum SST. Gray field represents the extreme winter El Ninõ events.

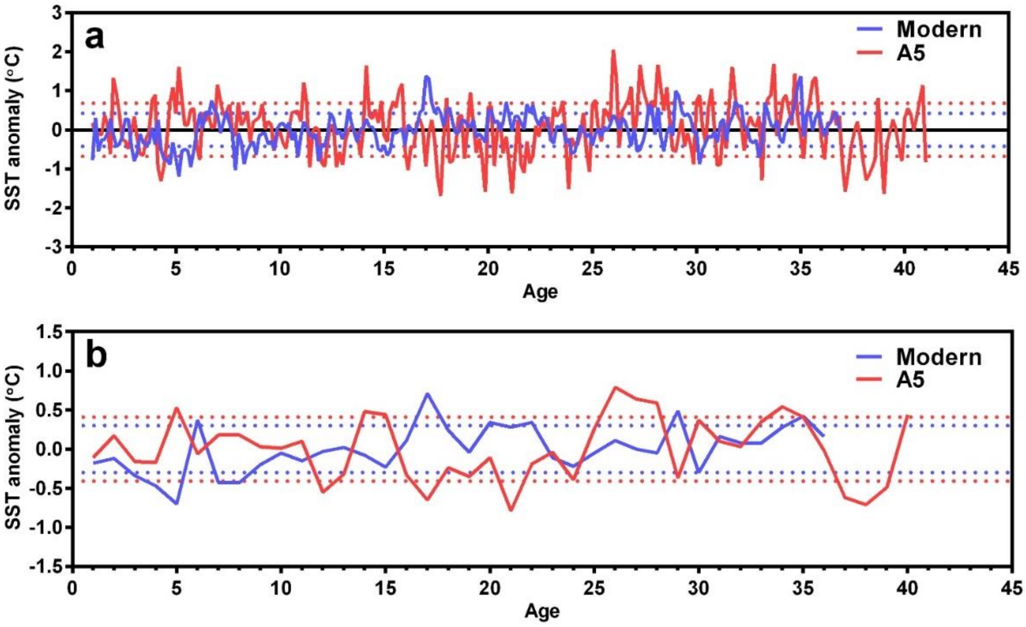

Figure 6. SST anomalies of modern instrumental data and reconstructed SST anomalies of *Tridacna* A5 under r-monthly (a) and r-annual (b) resolution. Dotted lines represent one standard deviation (1σ) of SST anomalies.

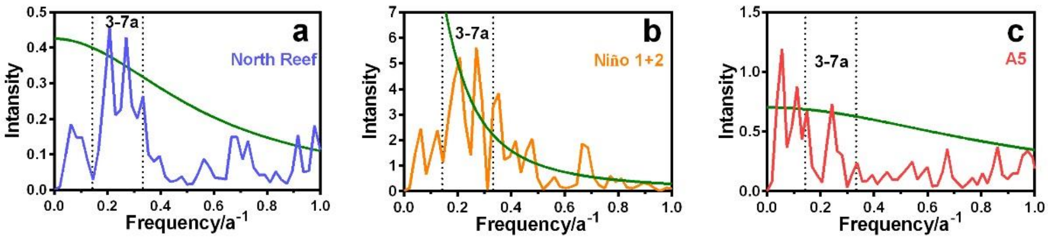

Figure 7. Spectral analysis of the North Reef SST anomalies (a), Ninõ 1 + 2 SST anomalies (b), and reconstructed SST anomalies according to $\delta^{18}O_{A5}$ (c). Green lines indicate significant lines at 90 % confidence level, and the area between two dotted lines represents the frequency from 3 to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

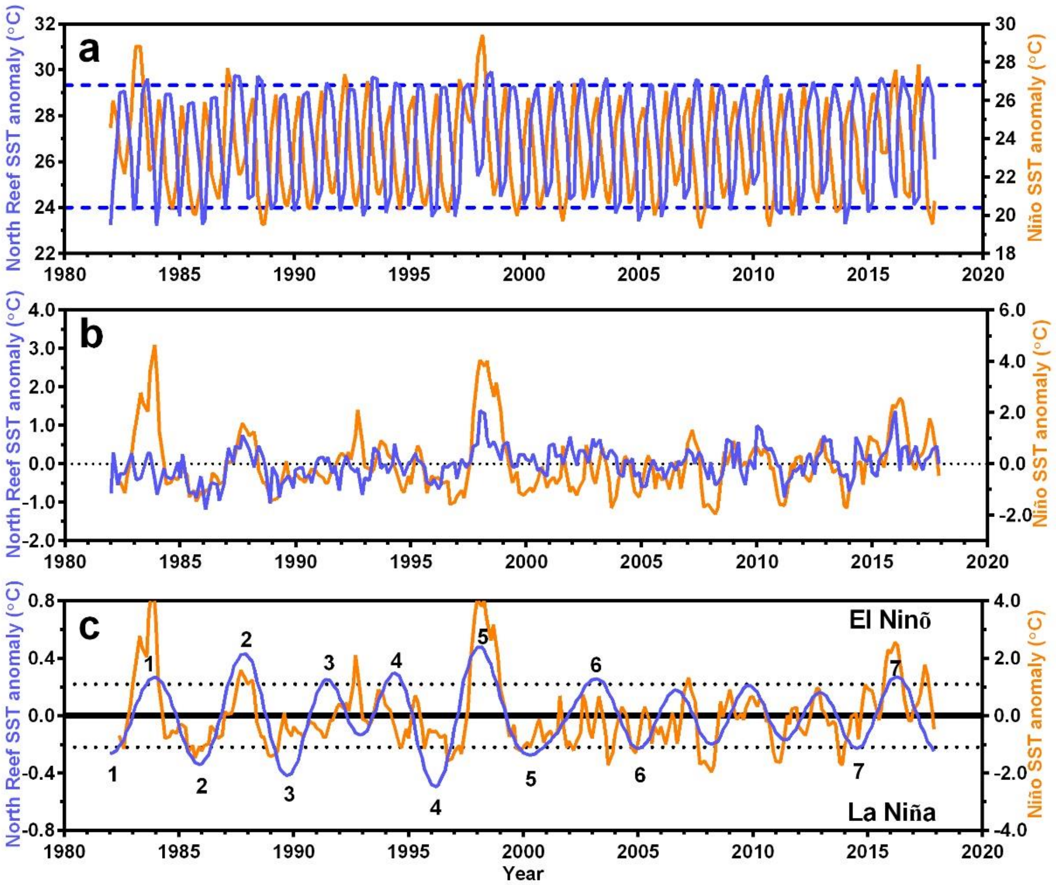

Figure 8. Relationship between Ninõ 1 + 2 SST and the North Reef SST: (a) The North Reef SST (blue line) compared with Ninõ 1 + 2 SST (yellow line), a clear time lag exists. (b) SST anomalies of two areas, and the lag is removed by forwarding the North Reef SST anomalies for 3-r-months. (c) The North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

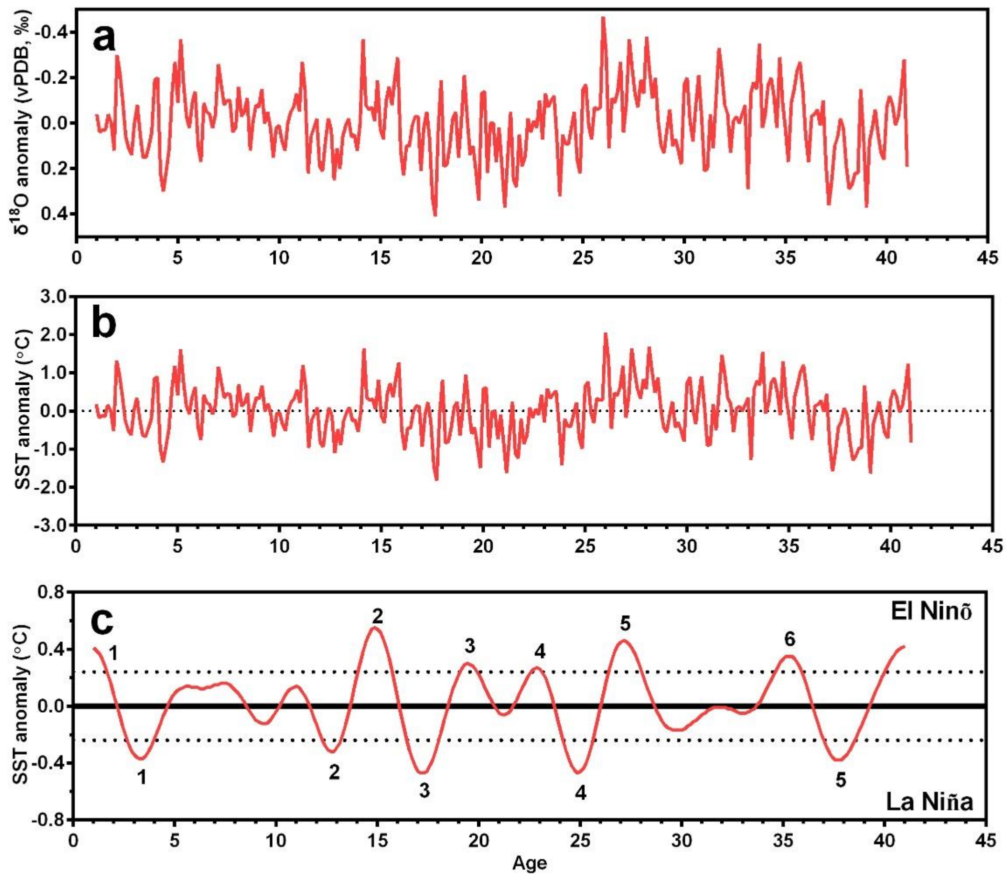

Figure 9. (a) ENSO activity reconstructed by fossil *Tridacna* 3700 years ago: δ^{18}O anomalies of fossil *Tridacna* A5. (b) The North Reef SST anomalies calculated by δ^{18}O anomalies, based on modern *Tridacna* δ^{18}O-SST equation (1 ‰ $\delta^{18}O_{shell}$ ≈ 4.41°C SST). (c) ENSO activity according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