Extreme weather events recorded by daily to hourly resolution biogeochemical proxies of marine giant clam shells

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Contributed by Zhisheng An, January 12, 2020 (sent for review September 26, 2019; reviewed by Wenju Cai and Mike Gagan)

Paleoclimate research has built a framework for Earth’s climate changes over the past 65 million years or even longer. However, our knowledge of weather-timescale extreme events (WEEs, also named paleoweather), which usually occur over several days or hours, under different climate regimes is almost blank because current paleoclimatic records rarely provide information with temporal resolution shorter than monthly scale. Here we show that giant clam shells (Tridacna spp.) from the tropical western Pacific have clear daily growth bands, and several 2-y-long (from January 29, 2012 to December 9, 2013) daily to hourly resolution biological and geochemical records, including daily growth rate, hourly elements/Ca ratios, and fluorescence intensity, were obtained. We found that the pulsed changes of these ultra-high-resolution proxy records clearly matched with the typical instrumental WEEs, for example, tropical cyclones during the summer—autumn and cold surges during the winter. When a tropical cyclone passes through or approaches the sampling site, the growth rate of Tridacna shell decreases abruptly due to the bad weather. Meanwhile, enhanced vertical mixing brings nutrient-enriched subsurface water to the surface, resulting in a high Fe/Ca ratio and strong fluorescence intensity (induced by phytoplankton bloom) in the shell. Our results demonstrate that Tridacna shell has the potential to be used as an ultra-high-resolution archive for paleoweather reconstructions. The fossil shells living in different geological times can be built as a Geological Weather Station network to lengthen the modern instrumental data and investigate the WEEs under various climate conditions.

Tridacna shell | daily growth bands | ultra-high resolution | biogeochemical proxies | weather-timescale extreme events

Weather-timescale extreme events (WEEs), such as tropical cyclones (TCs), cold/hot surges, rainstorms, droughts and more, usually occur on timescales of days or even hours, but nevertheless potentially cause great damage to the local socioeconomic and environmental systems (1–6). Thus, studying WEEs to increase understanding and prediction should be a priority. However, there are still many uncertainties in predicting the trends of WEEs, due to the relatively short time span, and limit coverage of modern instrumental data, especially for the oceans, and the deficiencies of numerical model simulations (2, 7). Paleoclimatic records often are an important supplement to modern measurement data, as they reveal the broader range in which many occur. Thus, reconstructing longer time span WEEs using natural archives could help understanding of the nature of WEEs and predict their future trends (12). However, the time resolutions of current natural paleoclimatic archives, from millennial to monthly at best, are too low to explore the range of past WEEs (7, 12). Therefore, our knowledge on the status of past WEEs under various climatic contexts is poor, although we have reconstructed Earth’s climate change framework over the past 65 million years or more.

The marine bivalve, Tridacna spp., the largest bivalve species in the oceans, is a prominent member of the Indo-Pacific coral reef communities from the Eocene (about 55 to 33 million years ago) to the present (13). It grows rapidly and can grow up to 1 m in length in a few decades to a hundred years (13). It usually stays in one location of a coral reef during its lifetime without any movement and thus accumulates a record for a point in space. Tridacna spp. have hard and dense aragonite shells with visible annual growth lines in their inner shell layer, and have been widely used in monthly resolution-scale tropical paleoclimatic research.

Significance

Reconstructing past extreme weather events, such as tropical cyclones and cold surges, using natural paleoclimate archives can lengthen the instrumental data and help us to have a broader understanding of the range of weather variability not evident in instrumental record. However, the time resolution of current paleoarchives, from millennial to monthly at best, is usually too low to explore past weather events. Here we found that the Tridacna shells from South China Sea, western Pacific, have continuous daily growth bands, and several daily to hourly resolution biogeochemical proxy records were developed. Our results demonstrate that these records can record nearby tropical cyclones and cold surges, indicating that Tridacna shells have the potential to be an unprecedented ultra-high-resolution archive for paleoweather reconstructions.

Author contributions: H.Y., Z.A., and W.Y. designed research; H.Y., C.L., H.F., X.M., G.S., J.H., and Yanan Yang performed research; H.Y., C.L., W.Y., S.Q., P.Z., and N.Z. analyzed data; and H.Y., Z.A., Yuanjian Yang, P.H., S.Q., J.D., K.Y., G.W., Z.J., and W.Z. wrote the paper.

Reviewers: W.C., Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research; and M.G., University of Queensland.

The authors declare no competing interest.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1916784117/-/DCSupplemental.

First published March 16, 2020.
(14–20). Using microscope and scanning electron microscopy (21–24), some studies have shown that Tridacna shells even have daily growth bands, implying that the Tridacna shells have the potential for reconstruction of the past WEEs.

In this study, a live Tridacna shell (Tridacna derasa, named XB10), 24.5 cm in length and 13 cm in width, was collected from the North Reef (17°05′N, 111°30′E) of the northern South China Sea (SCS) on December 9, 2013 (Fig. 1 A and B). The North Reef is a tropical elliptic coral reef without a land connection (SI Appendix, Fig. S1). The modern climate of the sampling site is dominated by the Asian monsoon, with hot, wet summers and cool, dry winters (SI Appendix, Fig. S2). The local extreme weather systems are frequently dominated by TC activities during the boreal summer−autumn periods and by cold surges during the boreal winter (Fig. 1A and SI Appendix, Fig. S2).

The XB10 was collected from the inner reef flat of the North Reef in a water depth of ~2.5 m during the high tide level (SI Appendix, Fig. S1). After preparation (SI Appendix, Methods), a laser scanning confocal microscope (LSCM; SI Appendix, Methods) was used on the 12.6-mm radial growth part of the Tridacna shell to obtain the autofluorescence microimages of the accumulation history of the carbonate shell (Fig. 1D and SI Appendix, Fig. S3). The elemental compositions of Sr, Ca, Ba, Mn, and Fe along the growth axis of the inner layer part were obtained by a laterally high-resolution secondary ion mass spectrometer (NanoSIMS; SI Appendix, Methods) with a distance of 12.6 mm and at 2-μm intervals from the inner edge (22) (Fig. 1D and SI Appendix, Figs. S4–S6).

Results

The autofluorescence images of the XB10 presented clear daily growth bands, and each daily band includes a couplet of bright and dark sections (Fig. 1E and SI Appendix, Fig. S5). The width of the daily bands ranged from 10 μm to 30 μm. In addition to the daily bands, the fluorescence intensity of the shell also presented some striking bright stripes (Fig. 1F and SI Appendix, Fig. S3). The Sr/Ca ratios show clear daily cycles during the whole 12.6-mm growth lifetime, and each Sr/Ca cycle corresponds well with the daily growth band (Fig. 1E). About 5 to 15 elemental data values can be obtained from each daily growth band, resulting in a time resolution of hourly intervals (22).

Based upon the daily growth bands and Sr/Ca daily cycles, together with the collected date (on December 9, 2013), the daily resolution chronology was established for the lifetime of the XB10 (SI Appendix, Methods). The total growth lifetime of the XB10 (0 mm to 12.6 mm) was 680 d, from January 29, 2012 to December 9, 2013. Then, the daily growth rate (DGR) and DGR variance (DGRV) profiles of the XB10 were calculated from the width of each daily band and the data volumes of each Sr/Ca daily cycle (Fig. 2 and SI Appendix, Methods and Fig. S7). The daily to hourly resolution Sr/Ca, Fe/Ca, and fluorescence intensity profiles were also established with the chronology. The climatic implications of these ultra-high-resolution proxy records, especially their potential in tracing the past WEEs, are discussed (SI Appendix, Texts).

Discussion

The DGR profile of the XB10 reveals many abrupt changes, especially during the boreal summer and autumn periods (Fig. 2).
In comparison with the instrumental data, it is found that these abrupt decreases of DGRs during the summer–autumn periods usually occurred together with TC episodes (Fig. 2 and SI Appendix, Fig. S8). The abrupt decrease of the *Tridacna* DGR might result from the reduced photosynthesis caused by the perturbations of the weather, because the growth of *Tridacna* mainly depends on the photosynthesis of symbiotic zooxanthellae (13, 25). The modern instrumental observations showed that the major weather perturbations during the summer–autumn periods in the northern SCS were TCs and rainstorms, which usually occur together (SI Appendix, Fig. S2). The strong wind, high sea wave action, ocean surface cooling, and rainy and cloudy conditions caused by TCs (SI Appendix, Figs. S2 and S8) would hinder the growth of *Tridacna*, resulting in a decrease in the daily growth increment (24). Thus, the rapid decreases of DGR of the *Tridacna* shell during the summer–autumn periods have the potential to be used as a proxy of TC activity.

To verify the effectiveness of using DGRs to reconstruct TC activity, we define a Local TC Index (LTI), which takes into account both the TC category and the distance between the TC and sampling site, to reflect the impact of TC on regional weather conditions and upper ocean environments (SI Appendix, Methods and Table S1). A higher LTI means a stronger TC impact. An LTI of over 10 is defined as a significant TC impact on regional weather conditions and ocean biophysical processes (SI Appendix, Methods). Meanwhile, a DGRV of less than −0.15 is defined as a significant decrease in DGR by more than 15% (SI Appendix, Methods). During summer–autumn of both 2012 and 2013, a total of 32 TCs with an LTI of >10 occurred, and 31 of them (96.9%) resulted in a decrease by at least 15% in the DGR of the *Tridacna* XB10 (SI Appendix, Fig. S8). Similarly, on 35 occasions, we registered that at least a 15% decrease of DGR occurred in the same periods, and 31 of them (88.6%) corresponded to TC activities (SI Appendix, Fig. S8).

In addition to growth rate, the pulsed peaks of Fe/Ca ratios were also highly correlated with the TC activities during the summer–autumn periods (Figs. 2 and 3). The vertical distributions of oceanic trace nutrient elements have an increased concentration from the surface to the subsurface (24, 26). The enhancement of vertical mixing during the TC activities around the North Reef could bring Fe-enriched subsurface seawater to the surface, leading these elements to rise abruptly in the surface seawater and then be recorded in the daily layer of the *Tridacna* shell (24, 26–29). Thus, the pulsed Fe/Ca peaks of the *Tridacna* shell during the summer–autumn periods could be used as a further potential proxy of TC activity (Fig. 3). Based on the LTI threshold, 31 TCs, which accounted for 96.9% of total TCs during the TC seasons (summer–autumn) of 2012 and 2013, resulted in relatively higher peaks of Fe/Ca ratios over 3.2E-04 in the *Tridacna* XB10 shell (Fig. 3). Similarly, a total of 31 peaks in Fe/Ca ratios of >3.2E-04 occurred during the summer–autumn of 2012 and 2013, and 28 of them (90.3%) corresponded well to TC occurrences (Fig. 3). Only three peaks in Fe/Ca ratio of >3.2E-04 were not caused by TC activities during the summer–autumn of both 2012 and 2013.

We further found that the Fe/Ca peaks of the XB10 were well matched with the striking bright stripes of fluorescence intensity in the microimages obtained by LSCM (Fig. 1F and SI Appendix, Figs. S9 and S10). Many previous studies have demonstrated that the transport of nutrients from the subsurface to the surface due to the increased vertical mixing during TC activity could result in phytoplankton blooms and even dissolved organic matter and detritus enhancements at the sea surface layer in the SCS (24, 26–29) (see SI Appendix, Fig. S11 for an example of phytoplankton bloom caused by TC activity). Consequently, the phytoplankton bloom with the increase of dissolved organic matter in surface seawater probably leads to higher organic matter content and stronger fluorescence intensity in *Tridacna* shells. The close matching relationship between striking bright stripes of fluorescence intensity and Fe/Ca pulsed peaks in XB10 (Fig. 1F and SI Appendix, Figs. S9 and S10), as well as the TC activities, demonstrate that the fluorescence intensity in *Tridacna* shell also has the potential to be used as a TC activity proxy.

TC is one of several WEEs, and assessing the trend of TC under global warming expectation is one of the most focused scientific issues in climatology in the past few decades, but the progress is a source of debate (5, 6, 8–11, 30). Investigating past TC activities using paleoarchives thus becomes very important. The variations of *Tridacna* XB10 growth rate, together with the Fe/Ca ratios and the fluorescence intensity, provide multiple lines of robust evidence that the daily to hourly biological and geochemical records from *Tridacna* shell in North Reef could be used to reconstruct past TC activities. With a passing TC, the growth rate of *Tridacna* shell would decrease abruptly due to the strong wind, large sea waves, heavy rainfall, and little insolation. The enhanced vertical mixing during the TC would bring nutrient-enriched subsurface water to the surface, enhancing the
Fe and nutrient concentrations with phytoplankton bloom in surface seawater and resulting in a high Fe/Ca ratio and strong fluorescence intensity in the carbonate shell of *Tridacna* (see SI Appendix, Fig. S10 for a sketch map). In addition to tracking the number of TCs, the proxy records also showed the potential for quantitative reconstruction of TC intensities. For example, the LTI shows significant interannual differences, which were stronger in summer–autumn of 2013 than in 2012 (Fig. 2E). Correspondingly, the reduction magnitudes in growth rates were usually greater (with lower DGRV) and the Fe/Ca values were often higher in 2013 than in 2012 (Fig. 2G and H). The LTI and *Tridacna* proxy records also present variations within a year. For instance, the DGRV declined and the Fe/Ca ratios increased gradually from June to November of 2013 in response to the increased LTI (Fig. 2).

Although it is difficult to distinguish the intensity, location, and path of a TC from the reconstruction of a single sampling site, our results imply that it would be theoretically possible to quantitatively reconstruct the frequency, path, and intensity of TCs in the western Pacific if we collect *Tridacna* samples from different coral reefs and conduct parallel research in this region. That is, it is essential and challenging for us to reconstruct quantitative TC information from the networks of *Tridacna* ultra-high-resolution proxy records in the northwest Pacific Ocean or even larger-scale regions in the future. In addition, cross-referencing different sampling sites may allow us to better explore the relationships between TC intensity/location/path and *Tridacna* proxy records.

In contrast to the TC activities during the summer–autumn periods, the modern instrumental observations also showed that the major weather/climate perturbations in the northern SCS during the winter are cold surges (31, 32). Strong winter cold surges from Siberia across the China mainland usually bring severe cooling, strong winds, and cloudy and rainy weather conditions in the northern SCS (31). During the winter season from December of 2012 to March of 2013, a total of five cold surges hit the northern SCS (Fig. 4). During these cold surges, the maximum decrease in surface air temperature reached 3°C to 6°C (Fig. 4), usually accompanied with strong winds over 20 km/h (SI Appendix, Fig. S2). The DGR of *Tridacna* shell was observed to decrease significantly during the five cold surges (Fig. 4), demonstrating that the unfavorable weather conditions caused by the winter cold surges also could hinder the growth of *Tridacna* shells. As during the TC events, the Fe/Ca ratios also increased during the five cold episodes (Fig. 4). Increased wind speed during the cold surges in winter could also enhance vertical mixing in the upper ocean and thus bring Fe-enriched subsurface seawater to the surface in the SCS (31–34), leading to raised Fe/Ca ratios and strong fluorescence intensity in the *Tridacna* shell. In addition, there are also some weak tropical storms that occurred together with cold surges during the winter between 2012 and 2013, leading to stronger responses in the proxy records of *Tridacna* shell XB10 (Fig. 4).

**Conclusion**

In summary, our results demonstrate that the clear daily growth bands observed by LSCM, together with the Sr/Ca daily cycles obtained by NanoSIMS, constitute accurate daily resolution chronology for the *Tridacna* shell collected from the northern SCS. The pulsed changes in the ultra-high-resolution biological and geochemical records from the *Tridacna* shell, including the DGR, Fe/Ca ratios, and fluorescence intensity, clearly recorded the activities of past WEEs, such as the TCs, marine phytoplankton bloom events, and cold surges, while still leaving us a few uncertainties or challenges (SI Appendix, Texts). Although the climatic implications of hourly *Tridacna* Sr/Ca ratios (many more proxy records can be developed, such as Mg/Ca, B/Ca, and more) remain unclear, the daily cycles imply that these elements/Ca ratios were likely to be associated with the diurnal weather/climate parameters (such as temperature, wind, solar radiation, etc.) and also have the potential to be used to trace the past WEEs of climate systems after careful calibrations.
The impacts of cold surges on the DGR, Fe/Ca ratio, and fluorescence intensity of the T. derasa XB10 during the winter between 2012 and 2013. (A) Anomaly of the daily maximum surface air temperature at the sampling site observed by the nearest weather station. (B) DGR profile of the T. derasa XB10 (DGR-XB10, three-point smoothing). (C) Fe/Ca profile of XB10. (D) Fluorescence intensity of the XB10. The top axis units apply to A–C. The bottom axis units apply to D. The blue shades indicate the five cold surges during the winter between 2012 and 2013 (SI Appendix, Methods). (E) Two tropical storms and one tropical depression, which had significant impacts (LT over 10) on the weather of the sampling site in this study, occurred together with the cold surges during the winter between 2012 and 2013.

Our results open a window to study the past WEEs using natural paleoarchives and suggest that *Tridacna* paleoweather records could be a useful vehicle for building the relationships between weather and climatic scales in paleoclimate researches. *Tridacna* are widely distributed in the coral reef systems of the Indo-Pacific tropical oceans (13). The fossil *Tridacna* samples under the different climate backgrounds have proven to be able to be collected from at least the Miocene (14–24) (see SI Appendix, Fig. S12 for dating results of collected subfossil shells from SCS). Meanwhile, using the oxygen isotope and elements/Ca, the fossil shells can provide monthly to decadal mean climatic conditions of shell growth stage and distinguish different seasons (14–24). The previous monthly resolution climate records, together with the daily to hourly proxy records developed in the present study (see SI Appendix, Figs. S13 and S14 for LSCM and NanoSIMS results of some other modern and fossil *Tridacna* shells from western Pacific), show that *Tridacna* shells have the potential to build robust Geological Weather Station networks in the tropical areas. Consequently, *Tridacna* shells will offer us the best chance to further investigate the WEEs variations in various climatic backgrounds, especially in the past warm and warming periods, which could help us understand the nature of the WEEs and predict their future frequencies and magnitudes.

**Methods**

*Tridacna* shell XB10 was cut to obtain a radial section. An LSCM was used to obtain the autofluorescence microimages of the shell, and NanoSIMS was used to obtain ultra-high-resolution elemental composition of Sr, Ca, Ba, Mn, and Fe. Then the daily resolution chronology was established, and several daily to hourly resolution proxy records, including DGR, DGRV, Sr/Ca, Fe/Ca, and fluorescence intensity, were obtained.

**SI Appendix, Methods** contains a detailed description of instrumental data, sample preparation, LSCM analyses, NanoSIMS analysis, Inductively Coupled Plasma Optical Emission Spectrometry analysis, daily resolution chronology, and the establishment of the DGR and DGRV time series.

**Data and Materials Availability.** All data are available in the manuscript or SI Appendix.

**ACKNOWLEDGMENTS.** This work was cosponsored by the National Science Foundation of China (Grants 41877399 and 41522305), Chinese Academy of Sciences, Chinese Ministry of Science and Technology, and Pilot National Laboratory for Marine Science and Technology (Qingdao). We thank Xiaopei Lin and Xianao Chen from the Ocean University of China and Xiaoil Qu from Xi’an Jiaotong University for their help in this work. H.Y. and W.Y. would like to thank the cooperation platform provided by the Youth Innovation Promotion Association of Chinese Academy of Sciences.

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