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High-frequency winter cooling and reef coral mortality during the Holocene climatic optimum

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Abstract

A detailed ecological, micro-structural and skeletal Sr/Ca study of a 3.42 m thick *Goniopora* reef profile from an emerged Holocene reef terrace at the northern South China Sea reveals at least nine abrupt massive *Goniopora* stress and mortality events occurred in winter during the 7.0–7.5 thousand calendar years before present (cal. ka BP) (within the Holocene climatic optimum). Whilst calculated Sr/Ca-SST (sea surface temperature) maxima during this period are comparable to those in the 1990s, Sr/Ca-SST minima are significantly lower, probably due to stronger winter monsoons. Such generally cooler winters, superimposed by further exceptional winter cooling on inter-annual to decadal scales, may have caused stress and mortality of the corals about every 50 years. Sea level rose by ~ 3.42 m during this period, with present sea-level reached at ~ 7.3 ka BP and a sea-level highstand of at least ~ 1.8 m occurred at ~ 7.0 ka. The results show that it took about 20–25 years for a killed *Goniopora* coral reef to recover.
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1. Introduction

Large, widespread and abrupt climate oscillations—some taking place within decades—have oc-curred repeatedly throughout geological records [1–3]. Characterization of such climate instability during interglacials is important for understanding triggers and anthropogenic impact on modern climate and for future predictions [2–4]. Compared with the bulk of the last glacial–interglacial cycle, the mid-Holocene has been known as a brief period of relative climatic stability [5] characterized by stabilized sea-level [6] and warmer sea-surface temperatures (SST) (at least in the Pacific) [7,8], ideal for prolific growth of massive

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corals in tropical oceans. However, recent studies highlight the mid-Holocene as a period of profound climatic change [1,9]. In this paper, we will report a detailed investigation of a 3.42 m thick Goniopora reef profile, which reveals decadal-scale climatic variability, resulting in cyclic mortality of flourishing corals during the "Holocene climatic optimum" in East Asia [10].

In addition, mass coral bleaching affecting thousands of square kilometres of coral reef has become an increasingly serious global environmental problem since 1990s, with global warming being blamed as the main cause [11]. This study provides the first pre-historic evidence for cold-temperature stress and mortality of reef corals at higher latitudes [12] and adds new dimension to the understanding of coral bleaching.

2. Field geology, stratigraphy and chronology

The Goniopora reef profile (20°14.005′N, 109°55.200′E) occurs within the reef-flat of an emerged fringing coral reef (10 km long, 500 ∼ 2000 m wide) at Leizhou Peninsula, northern coast of the South China Sea [13] (Fig. 1). The area is far away from subduction zones and is thus tectonically stable, and overall vertical movement during the Holocene is negligible relative to the magnitude of sea level change [14]. The area is part of the East Asian monsoon regime where episodic cold air outbreaks from the north can lead to anomalously low winter temperatures. Instrumental records show that the annual SST cycle in this area is up to 11 °C.

The emerged fringing reef, with its top surface elevation measured at an average 1.8 m above modern low spring tide [13], can be divided into five major morphological/ecological zones (Fig. 1). From sea to land, they are (1) reef-front living coral zone (10–120 m wide) with dominant Acropora corals growing below the low spring tide; (2) outer reef-flat massive Porites zone (100–150 m wide) dominated by large blocky Porites corals (5–6 m in diameter); (3) within-reef-flat mixed massive coral zone (∼ 200 m wide) consisting of large Porites, Pavona (8–10 m in diameter) and Favia corals; (4) within-reef-flat mixed massive-coral/Goniopora zone (0–120 m wide) with smaller massive corals mixed

with branchy Goniopora corals; and (5) inner reef-flat Goniopora zone (100–500 m wide) dominated by branchy Goniopora corals with a spatial coverage of >95%.

A total of four wells were dug at different locations within the inner reef-flat Goniopora zone [13]. The stratigraphical sequences revealed in all four wells are well correlated with each other. Overall, the reef profile is composed of nine layers of branchy Goniopora corals (Fig. 2), which occupy over 95% of the total volume. Their growth rates vary between 8.8 and 22.2 mm/year, with top six layers being much lower than the bottom two layers. Growth discontinuities between individual layers are well defined. Smoothed discontinuities between Goniopora layers are clear evidence for sudden death of such flourishing Goniopora in very short intervals. Only Layers 3–5 show evidence for emergence above the low spring tide, such as eroded surfaces and the presence of various species of oysters adhering to the Goniopora branches [13]. In these three layers, the Goniopora branches are short and irregularly shaped, reflecting depressed vertical growth environment. In all other layers, no erosions were observed, evidenced by well-preserved coral heads with continuous curved growth contours (see Fig. 2). In Layers 7–8, the Goniopora branches are thin and long, with round heads well preserved, reflecting relaxed vertical growth environment without tidal erosion. X-ray images of skeletons of those well-preserved Goniopora heads reveal that almost all the top surfaces (i.e. growth hiatuses) of the skeletons were composed of high-density dark bands (Fig. 2), suggesting that the Goniopora died in winter [13]. This is because microstructure analysis of modern Goniopora coral shows that high-density dark bands (lower growth rates) form in winter and low-density light bands (higher growth rates) in summer. The annual growth rates in these images do not show a gradually decreasing trend toward the top, also implying that the coral died suddenly.

Nine samples from this profile yielded conventional radiocarbon ages between 6.31 ± 0.14–6.67 ± 0.16 ^{14}C ka BP (2σ errors), corresponding to 6.79–7.26 cal. ka BP, if open-marine reservoir age correction is used [15]. Based on regression between the radiocarbon dates and depths of these nine samples, the ages for surface and bottom of this reef profile are
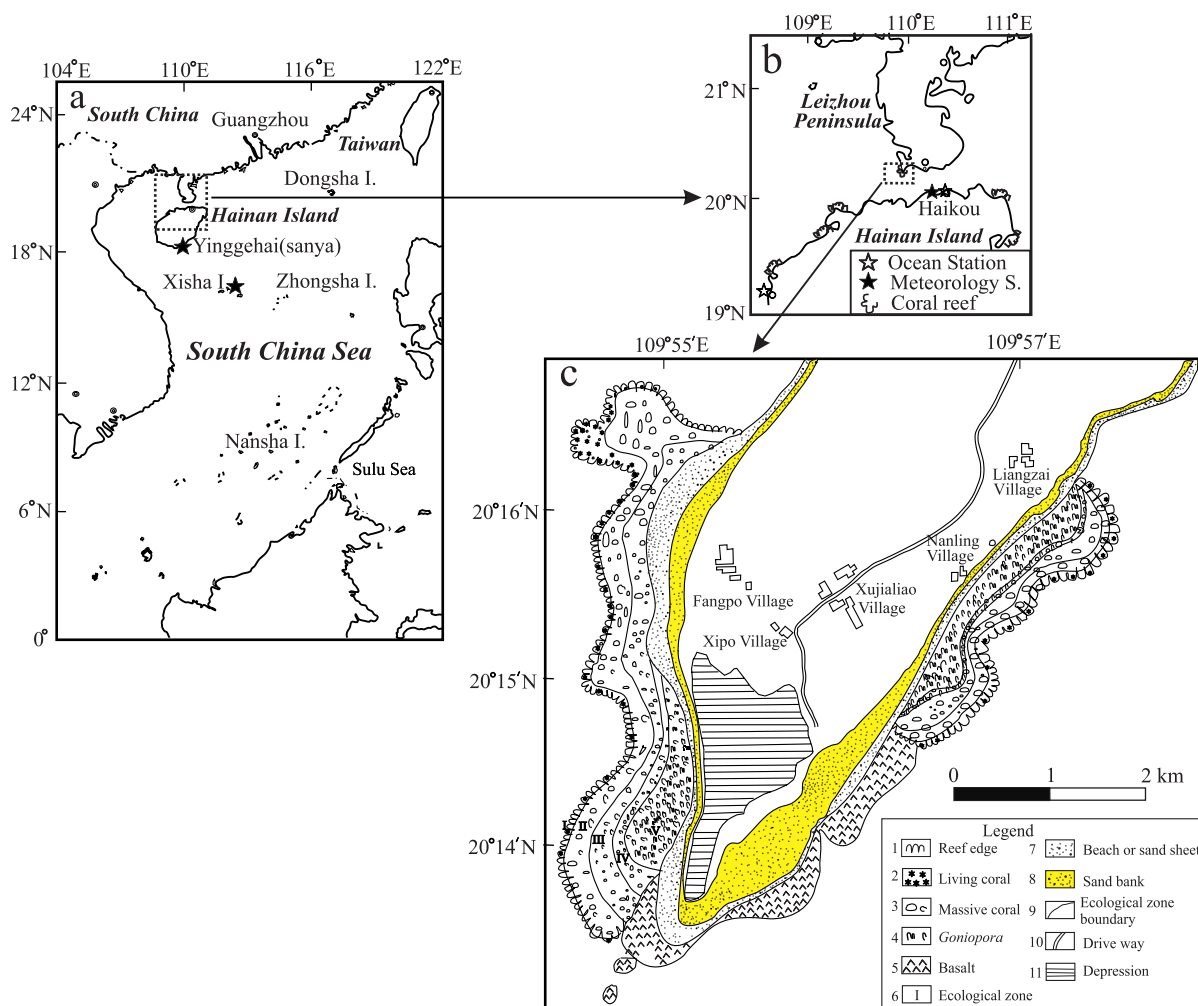
Fig. 1. Maps showing the locations of (a) the Leizhou Peninsula and (b) the Dengloujiao reef terrace, as well as (c) the distribution of morphological/ecological zones of the Dengloujiao reef terrace. Also shown are the Xisha, Yinggehai (Sanya) and Haikou meteorological stations.

6.3 ± 0.2 and 6.7 ± 0.2 ^{14}C ka BP, corresponding to calendar ages of 6.8 and 7.3 ka BP, respectively. In addition, we have also attempted to use U-series dating to cross-check the reliability of our radiocarbon chronology. Due to high detrital components in these *Goniopora* samples, their detrital-correlated U-series ages have large errors and are less reliable, but do fall in the range of 6.8–7.3 ka. However, replicate analyses of one clean massive coral of *Favia* genus coexisting with *Goniopora* corals from the second layer yields precise U-series ages of 6975 ± 58 and 7062 ± 71 years BP, with a weighted mean of

7008 ± 46 years BP. This age is 215 years older than calibrated radiocarbon age (6793 years BP) for the same sample, probably due to a different localized reservoir age in the South China Sea. In addition, a massive *Porites* sample immediately above the profile yielded a U-series age of 6680 ± 82 years BP, consistent with the stratigraphical sequence. Massive *Porites* and *Favia* corals are cleaner and less susceptible to alteration and U mobility and therefore often yield more precise and reliable U-series ages. Because of this, we further correct the calibrated radiocarbon dates by adding 215 years to these dates (see Fig. 3).
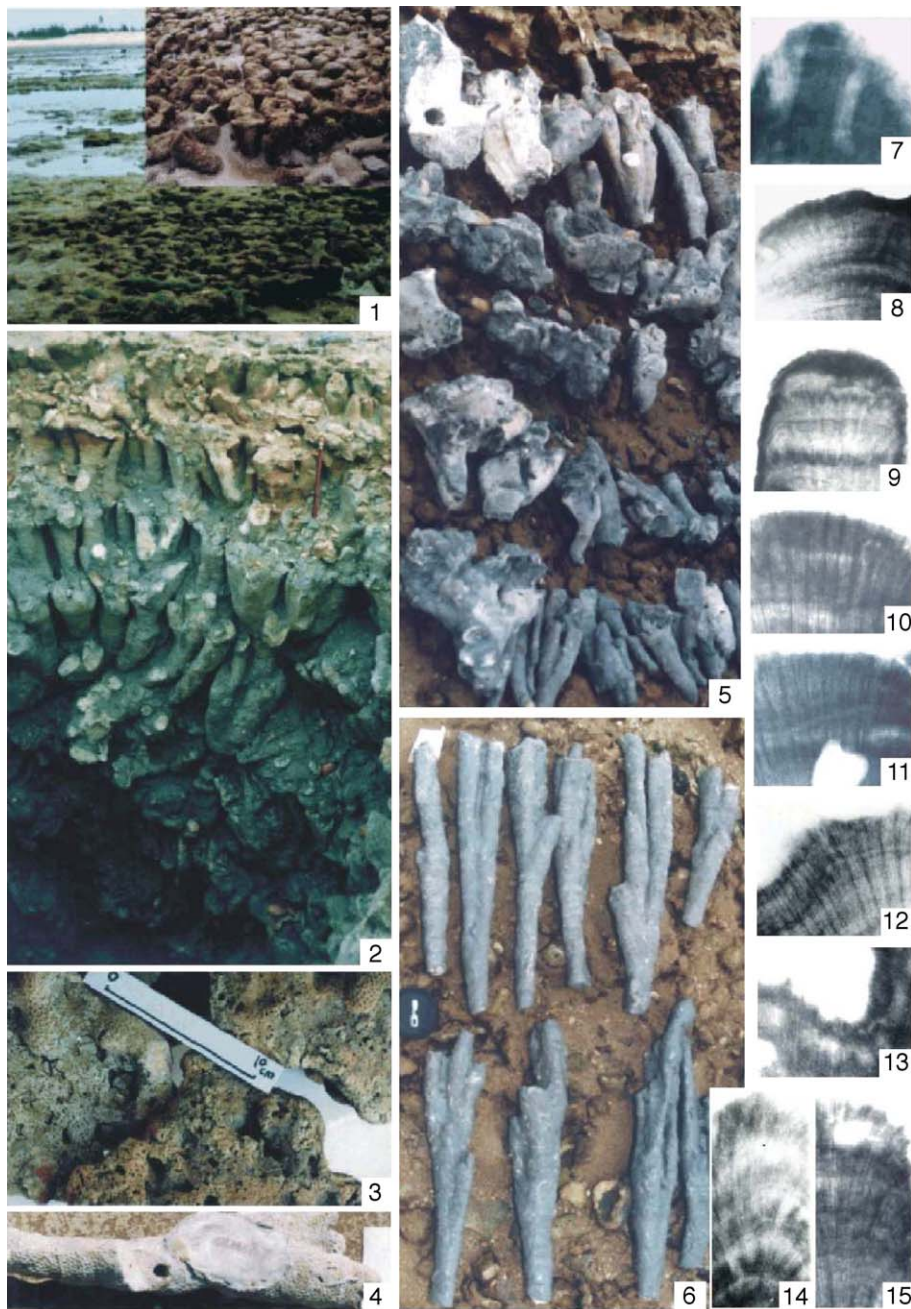
Fig. 2. Field distribution, structure and texture of *Goniopora* reef corals at Dengloujiao reef, Leizhou Peninsula. (1) *Goniopora* reef flat geomorphology showing it is emerged during low tide. (2) A 3.4-m-long *Goniopora* reef profile revealed in well DLW. (3) Examples of eroded *Goniopora* coral surfaces of Layers 3–5. (4) Oysters adhering to a *Goniopora* branch. (5) *Goniopora* samples from Layers 1a, 1b, 2–6. (6) *Goniopora* samples from Layers 7–8. (7–15) X-ray images of the top sections of coral skeletons from each layer (7–15 from Layers 1a–8, respectively). Note that dark high-density bands can be seen on the top parts of most images.

layer	Sampling Depth/cm	^{14}Cage (a BP)	TIMS age (a BP)	^{14}C cal.Age (a BP)	TIMS cal. age (a BP)
1a	6.5	6370±80	6680±82*	6860	7075
1b	23	6400±80		6916	7131
2	61	6305±70	7008±58	6793	7008
3	101	6310±70		6797	7012
4	129	6430±95		6948	7163
5	164	6460±75		6990	7205
6	208	6580±70		7186	7401
7	261	6600±70		7200	7415
8	311	6670±80		7260	7475

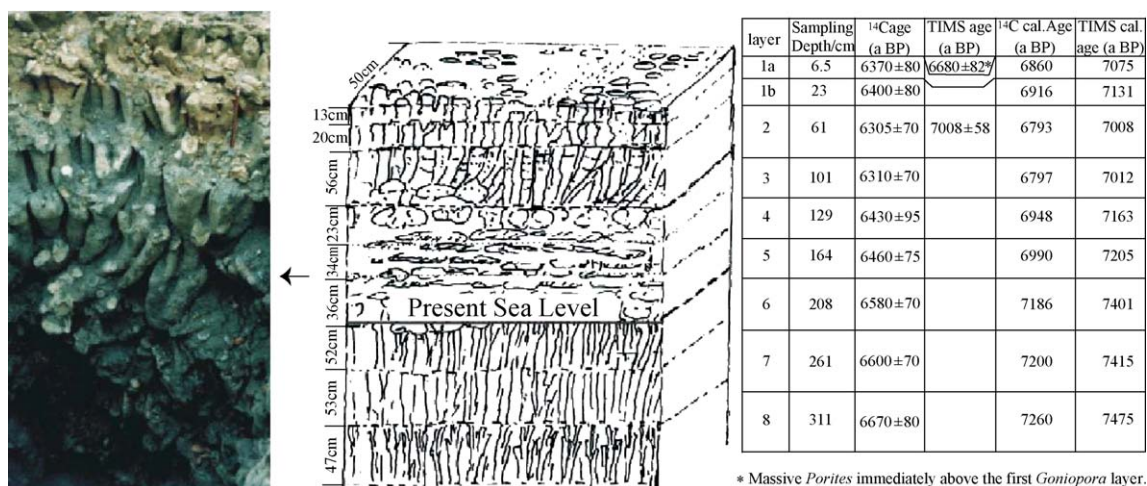* Massive *Porites* immediately above the first *Goniopora* layer.

Fig. 3. Cross section of *Goniopora* reef profile at Leizhou Peninsula. The whole section is composed of *Goniopora* corals, which can be subdivided into nine layers, with hiatus between layers clearly visible. *Goniopora* coral heads on tops of Layers 3, 4 and 5 are eroded. Also listed are measured ^{14}C (1σ error) and TIMS U-series (2σ error) dates, and their relative depths in the profile. Age values in ^{14}C cal. ages (years BP) column are in calendar years calibrated after [15]. Age values in the TIMS cal. age (years BP) are further corrected ages based on TIMS U-series date of 7008 ± 58 years BP for the *Favia* coral sample from Layer 2.

Thus, the corresponding regressed surface and bottom ages of the reef profile are 7.0 and 7.5 cal. ka BP, respectively.

3. Skeletal Sr/Ca results

We also collected five samples from the *Goniopora* profile (DLW-01-8 DLW-02-3 DLW-03-3 DLW-05-5 and DLW-08-1 from Layer 1, 2, 3, 5 and 8, respectively), which show well-preserved coral heads and no evidence for obvious erosion, together with a modern *Goniopora* for Sr/Ca analysis by ICP-AES following the method of Schrag [16]. For the modern *Goniopora*, a total of 50 samples were collected at fortnightly resolution. For the Holocene samples, the sampling resolution was at $10-15$ samples per year. A total of 263 sub-annual specimens were collected, with Holocene coral samples covering about $3-8$ years of growth history. The sub-annual specimens were analysed on an ICP-AES at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Detailed analytical procedures were described in [7,17]. The Sr/Ca results for the modern *Goniopora* sample display very clear inter-annual cycles, well correlated with

instrumental SST records from the Haikou station 50 km away (Fig. 4). Low-density bands deposited in summer have lower Sr/Ca ratios than high-density bands formed in winter. By matching the Sr/Ca data with instrumental SST records, the following relationship can be established using Isoplot/EX program [18]: SST (°C) = -32.8 (± 3.5) $\times$ Sr/Ca$_{(mmol/mol)}$ + 315 (± 31) (MSWD = 4.4, $r = -0.9999$, $n = 48$, errors quoted at 95% confident level), which is similar to those developed for *Porites lutea* at the same site [7]. The calculated Sr/Ca-SST uncertainty based on slope and intercept errors of the equation is ± 0.3 °C, which is smaller than the uncertainty of ± 0.58 °C based on the analytical precision of $\pm 0.2\%$ for Sr/Ca. Thus the overall Sr/Ca-SST uncertainty is less than ± 0.9 °C.

Fig. 5 illustrates Sr/Ca profiles for the Holocene *Goniopora* corals from different layers of the reef profile. The results show that all skeletal Sr/Ca of the Holocene *Goniopora* corals display very clear annual cycles, similar to the modern *Goniopora*. Sr/Ca data for the surface parts of all the *Goniopora* samples plot on the left limbs of convex curves leading up to the winter maxima, supporting the argument [13] that the *Goniopora* corals died in winter (note that, due to sampling difficulty, the very top parts of some
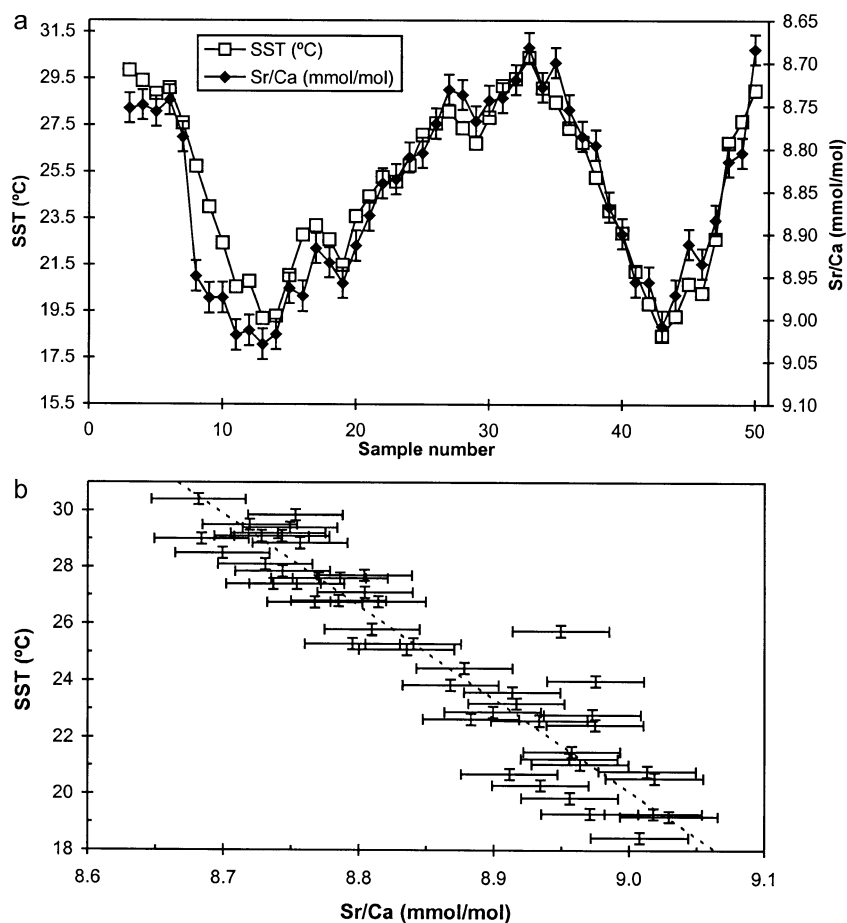
Fig. 4. Skeletal Sr/Ca variation of a modern *Goniopora* coral (open cycles) for comparison with instrumental SST records (solid cycles) (a) and linear regression of Sr/Ca against instrumental SST (b). Nominal errors of ± 0.2% for Sr/Ca and ± 0.1 °C for instrumental SSTs (interpolated from monthly SST records) were used in the regression and the plots. Using Isoplot/EX program of [18], the following regression equation can be obtained: $SST(°C) = -32.8 \ (\pm 3.5) \times Sr/Ca_{(mmol/mol)} + 315 \ (\pm 31)$ (MSWD = 4.4, $r = -0.9999$, $n = 48$), where MSWD—Mean square of weighted deviations; *r*—correlation coefficient.

dead coral heads, e.g. DLW-01-8, DLW-03-3 and DLW-05-5, are not available for analysis). Sr/Ca cycles in Fig. 5 also suggest that large-amplitude cooling did occur, resulting in high skeletal Sr/Ca anomaly on inter-annual scale. Comparing the Sr/Ca-SST data for sample DLW-02-3 that covers a period of 6.5 years, with monthly instrumental SST records for 1994–2000 obtained from the Haikou station 50 km away (Fig. 5), the following important features can be obtained: (1) Annual Sr/Ca-SST maxima for DLW-02-3 are relatively stable, with a mean of 30.5 °C, identical to that of the instrumental SST maxima

(30.3 °C) for January 1994 to December 1999. (2) The mean value of annual Sr/Ca-SST minima for DLW-02-3 is 15.1 °C. If the value for Year 6 is rejected, the mean is 16.0 °C, which is still 3.1 °C lower than the mean of the instrumental SST minima for September 1994 to June 2000 (19.1 °C). (3) Exceptionally low Sr/Ca-SST minimum of 10.7 °C was recorded for Year 6, which is ∼ 5 °C lower than in the other years. The corresponding Sr/Ca-SSTs for the other four *Goniopora* samples that cover shorter periods are also shown in Fig. 5, which are basically comparable to those for DLW-02-3.
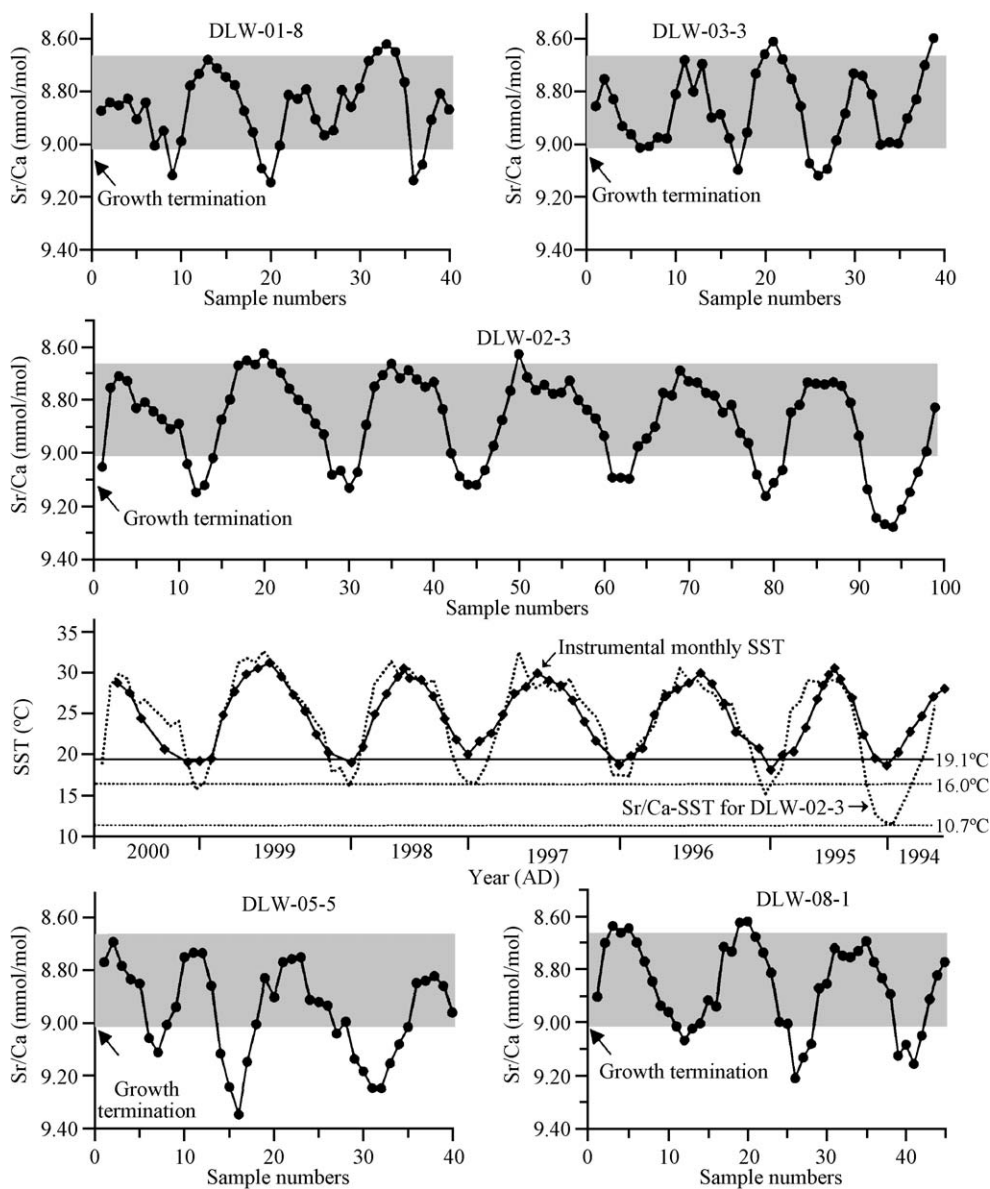
Fig. 5. Skeletal Sr/Ca data for the Holocene *Goniopora* coral samples from Layers 1, 2, 3, 5 and 8 of the reef profile. All Sr/Ca sub-samples for each coral were collected sequentially from the surface downwards and thus Sample No. 1 on the left end of each Sr/Ca profile is closest to (but not exactly on) the very top surface of each coral, which has a non-eroded dead head. The calculated SST curve for DLW-02-3 is also shown for comparison with instrumental monthly SST records in the 1990s obtained from the Haikou meteorological station ∼ 50 km away. Shaded areas in other figures illustrate the modern instrumental SST range. Please note that (1) all corals stopped growth at the transition to winter based on Sr/Ca trends and (2) the inter-annual mean of winter minima and Year-6 winter minimum in DLW-02-3 is 16.0 °C and 10.7 °C, which are 3.1 °C and 9.6 °C lower than the mean winter SST in the 1990s, respectively. See text for discussion.

4. Discussion

4.1. Interpretation of Sr/Ca-SST records

The weight of abundant evidence now indicates that coral Sr/Ca can be a highly reliable SST proxy independent of the extension rate or salinity change, with an overall accuracy of ~ 1 °C for most of the tropical oceans [8,19–23], except for some upwelling zones such as the Eastern Pacific where local artefacts may be produced by upwelling of deep ocean water with an unusual Sr/Ca ratio [24]. However, in situations where SST drops below 18 °C, possible coral metabolic changes and/or inorganically controlled aragonite-seawater fractionation may incur non-linear response of Sr/Ca to SST, resulting in amplifications of the SST anomaly [22,25]. The calculated Sr/Ca-SST results in our study indicate that, whereas the Holocene Sr/Ca-SST maxima are similar to those in 1990s (average ~ 30.5 °C vs. ~ 30.3 °C), the Holocene Sr/Ca-SST minima for sample DLW-02-3 are on average ~ 3 °C lower (~ 16.0 °C vs. ~ 19.1 °C), with Year 6 (10.7 °C) being ~ 8.4 °C colder. Such lower than expected Sr/Ca-SST minima are unlikely to be real, but possibly due to non-linear response of Sr/Ca to cool SSTs [22,25]. However, even if a 2 × amplification factor is assumed [22], the actual average of the SST minima would still be ~ 1.5 °C colder than in the 1990s, with Year 6 being ~ 15 °C, ~ 4 °C colder than in the 1990s. Thus despite the inaccuracy in the low SST range, the overall trend does suggest that the Holocene SST minima are indeed significantly lower than in the 1990s (Fig. 5).

It may also be argued that the Sr/Ca-SST calibration equation, which is based on a short growth history of a modern *Goniopora*, may not adequately reflect the longer-term SST-Sr/Ca relationship. However, the degree of correlation between Sr/Ca and instrumental SST in our calibration is as good as most other published relationships based on TIMS Sr/Ca data [20,23,26]. For well-correlated Sr/Ca-SST relationships in the published calibrations, calibration equations regressed from parts of the dataset are basically similar to that based on the whole dataset. In fact, in our situation, even if the first less well-matched 13 data from the top part of the coral sample are removed, the regression based on the remaining perfectly matched data still yields a similar equation: SST $(°C) = -34.2$ $(\pm 3.2) \times$ Sr/Ca$_{(mmol/mol)} + 327$ (± 29) (MSWD = 2.4, $r = -0.9999$, $n = 35$). Based on this new equation, the calculated SSTs for the Holocene samples are only marginally lower (by average ~ 0.4 °C with a larger influence on winter SSTs), which will not affect (if not enhance) our argument for a colder winter in the mid-Holocene.

4.2. Causes of Goniopora coral mortality in the mid-Holocene

Coral mortality can be attributed to a number of causes: (1) destruction from natural calamities, including high SST and associated radiation leading to coral reef bleaching [11], freshwater input leading to low salinity [27], low SST leading to "cold bleaching" [12,28,29], extreme low tides or sea-level drops leading to emergence of corals [30], and severe storms [31]; (2) predation [32]; (3) destruction by human activities [33]; and (4) disease [34].

Regardless of the calibration equations we choose or the uncertainties in the calculated Sr/Ca-SST values, the Sr/Ca-SST trends for all the measured samples in this study (Fig. 5) strongly indicate that growth of all the *Goniopora* corals terminated at the transition to winter, implying "cold bleaching" [12] as the main cause of mortality. As described above, all the samples we selected for Sr/Ca analysis show well-preserved continuous growth contours that have not been disturbed by tidal erosion. This suggests that the last few Sr/Ca analyses represent growth bands forming during the last few months or weeks prior to their sudden death. This inference is also strongly supported by microstructural examination of the *Goniopora* skeletons (Fig. 2) which shows that the growth termination is within the high-density dark bands.

The alternative causes of coral mortality, except for sea-level fluctuations, can be easily ruled out. For instance, freshwater input from floods, severe storms or high-temperature bleaching are unlikely simply because the corals died during the winter season. There is also no evidence for disease or predation. Human activity was impossible at this time.

Sea-level fluctuations might be an alternative cause of coral mortality. Since each layer of the in situ *Goniopora* reef (Fig. 3) could at most grow to the low spring tide, the seriously eroded *Goniopora* surfaces

within Layers 3–5 clearly suggest that they were briefly emerged after their development below the low spring tide level. The presence of various species of oysters adhered to each layer of the *Goniopora* reef also indicates that the reef reached the inter-tidal zone after their development in the subtidal zone.

However, we argue that winter cooling was the main cause of the *Goniopora* mortality, with sea-level-controlled emergence only playing a secondary role. Evidence supporting this argument includes: (1) Layers 1, 2, 6, 7 and 8 show no signs of emergence or erosion, and the top surfaces of these layers are well preserved (Fig. 2), yet mortality still occurred in these layers. (2) The growth behaviour of Layers 7–8 suggests the development of *Goniopora* corals was not suppressed by too shallow water depth (Fig. 2). (3) The annual extension rates for all samples we examined show no progressive slow-down in the top sections leading to growth termination but progressive slowdown of growth would be expected during a sea-level lowering process. (4) It is extremely unlikely that all sea-level lowering events occurred in winter as reflected by Sr/Ca and microstructural evidence.

"Cold bleaching" and mortality of branchy reef corals during the winter months may be a natural phenomenon for high latitude coral reefs where winter SST may frequently drop below 18 °C [12,28,29]. In fact, similar cold bleaching and mortality of branchy *Acropora* coral colonies occurred on 5 August 2003 at Heron Island, the southern end of the Great Barrier Reef [29], when local air temperatures dropped to as low as 12 °C. Similarly, coral mortality occurred in the Arabian Sea when the monthly mean SST there dropped to < 13 °C [28]. In the northern South China Sea, instrumental records over the past 40 years (1961–2001 AD) indicate that winter SSTs display much larger temporal and spatial variations than summer SSTs. For instance, the means of monthly summer SST maxima from Haikou, Yinggehai (Sanya, Hainan Island) and Xisha meteorological stations of different latitudes are 30.3, 30.0 and 29.8 °C, respectively, very similar to each other. In contrast, the means of monthly winter SST minima from these locations are 18.4, 22.5 and 23.8 °C, respectively, which are significantly different from each other. Fig. 6 shows the deviations of annual winter minima/summer maxima from the 40-year means for SST records from the above stations. It can be clearly seen

that the winter minima are highly variable for records from all three stations, which also display inter-annual cyclicity to some extent. Among them, the coastal records (Haikou and Yinggehai) are more variable than the oceanic records (Xisha), probably due to stronger influence of winter monsoons on the coastal sites. At Haikou (only 50 km away from the sampling site), a chilling SST of 15.2 °C was registered in 1965/66 winter, which is 4.8 °C colder than in 1967/1968 winter (21.0 °C). A similar SST difference of 4.2 °C during the same period was also recorded in the Yinggehai record. It can be inferred that winter SST at the reef site of this study during the mid-Holocene might be as variable as in the last 40 years. Such a highly variable winter SSTs, with an inter-annual anomaly by up to 4–5 °C as shown in both the Holocene Sr/Ca-SST (Fig. 5) and the modern instrumental (Fig. 6) records, may be responsible for the episodic bleaching and mortality of the *Goniopora* corals.

4.3. Palaeoclimatic implications

The summer Sr/Ca-SSTs of all the measured mid-Holocene (7.0–7.5 ka BP) samples are comparable to those of the Haikou instrumental records in the 1990s only 50 km away from the reef site, suggesting this part of the mid-Holocene was a warm period, similar to the 1990s. However, both the winter Sr/Ca-SST means (∼ 16.0 °C for DLW-02-3) and the inter-annual winter Sr/Ca-SST anomalies (10.7 °C for DLW-02-3) recorded in these measured samples are significantly lower than those of the instrumental records for the last 40 years (18.4/15.2 °C), or the 1990s (19.1/18.2 °C). As discussed above, even if the non-linear response of coral skeletal Sr/Ca to low SST is taken into consideration, the winter SSTs in the mid-Holocene were still significantly cooler than in the present. We consider that this is probably related to stronger winter monsoons during 7.0–7.5 ka BP, resulting in a larger seasonality than present time. Lake-level and pollen records from north-central Chinese mainland shows that stronger winter monsoons did occur in China during 10–7 ka BP [35], and gradually moved to South China [10]. Recent studies of speleothem, loess and marine sediment records consistently show there was a clear climatic tele-connections between East Asian monsoon variability
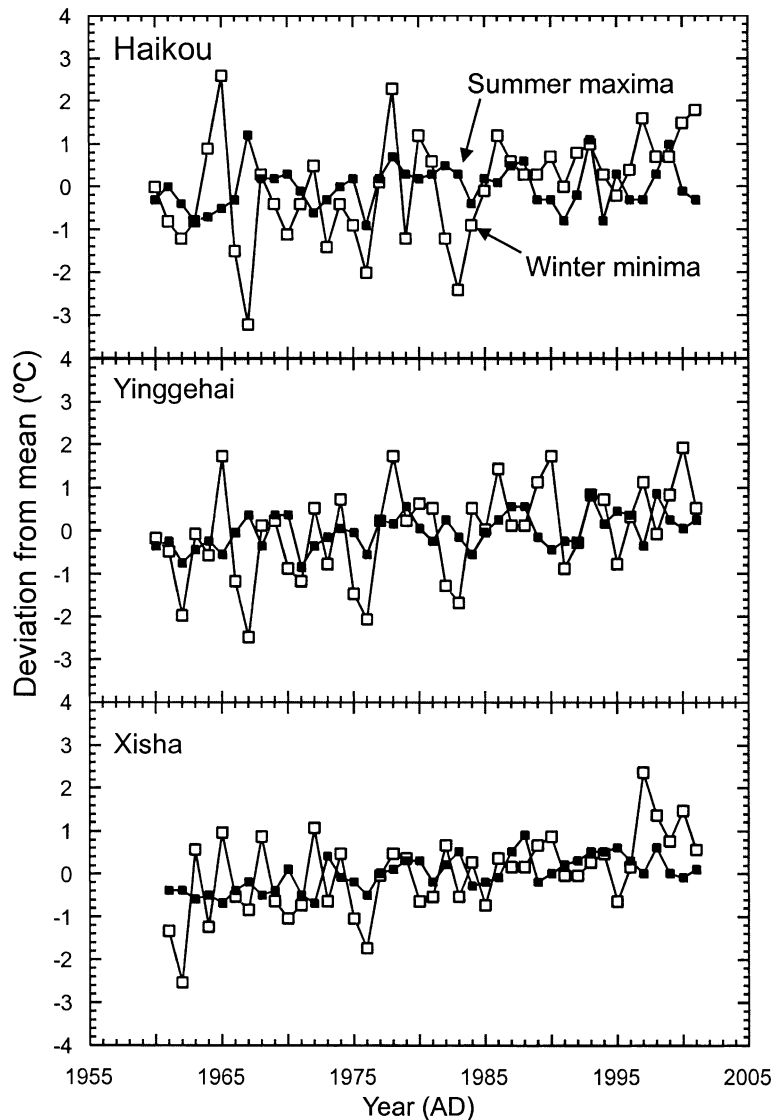
Fig. 6. Deviations of summer monthly SST maxima and winter monthly SST minima from their respective 40-year means based on instrumental SST records from Haikou (20°41.05′N, 109°59.18′E), Yinggehai (18°15′N, 105°25′E) and Xisha (16°50′N, 112°20′E) meteorological stations in the northern South China Sea. The winter SST's for all three stations are more variable than the summer SSTs, with inter-annual difference up to 4–5 °C observed in both Haikou and Yinggehai during 1965–1968. See text for discussion.

and North Atlantic air temperature change during the glacial period with winter monsoons being intensified and South China Sea surface temperatures lower when air temperature in the North Atlantic was reduced [36–39]. Our recent study also indicates that post-glacial Holocene coral growth and sea level change were in pace with millennial-scale ice-rafted debris

events in the North Atlantic [9,40]. Greenland ice core $\delta^{18}O$ record shows that the period of 7.0–7.5 cal. ka BP was characterized by an air temperature trough [41]. In this regard, we speculate that this low air temperature may have enhanced the Siberian High via atmospheric teleconnnections, resulting in strengthened winter monsoons in East Asia.

In addition to the implications for SST and East Asian winter monsoons, the *Goniopora* profile at Leizhou Peninsula also recorded detailed past sea-level change. Corals can only grow at waters below sea level and flourishing corals usually develop below the low spring tide level. Thus, the surface elevations of in situ reef corals are excellent indicators of palaeo-sea level [42,43].

The over 3.42 m thick *Goniopora* reef profile reflects a fast pace of sea level rise. Our field tide and bench level measurements indicated that the top surface (representing past low spring tidal level [44]) of this profile was ~ 1.82 m above the present low spring tidal level. This suggests that the present sea-level was reached at ~ 7.3 ka BP when the ~ 7.3 ka old *Goniopora* corals at the depth of 1.82 (Layers 5/6 boundary) was formed, and a sea-level highstand of at least ~ 1.8 m was reached by ~ 7.0 ka ago (the upper age limit of the reef profile). Such estimates of sea levels are consistent with those defined by U-series dated *Porites* corals from the same reef terrace [40], as well as those from elsewhere in the southeast Asia [45].

Assuming a linear sea-level rise curve during this period, an average sea-level rise rate of 6.6 ± 2.8 mm/year can be obtained from the best-fit line defined by the calibrated radiocarbon dates of the nine *Goniopora* samples and their relative depths. However, the sea level rise during this period was not smooth, but punctuated by several hiccups or even lowering events. This is because multiple emergences and erosions of *Goniopora* coral heads occurred within Layers 3−5 of the reef profile. The presence of various species of oysters adhered to *Goniopora* branches within Layers 3−5 also indicates that the reef reached the inter-tidal zone after their development at the subtidal zone.

Based on measured average extension rates of *Goniopora* corals in individual layers, we calculated that the total 3.42 m thick profile represents a growth history of ~ 276 years, plus some period for the growth of the eroded portions within Layers 3−5. Considering the fact that the whole profile was formed during 7.0−7.5 ka BP, or a period of ~ 500 years, the total duration of growth hiatus is about 200 years, or the growth hiatus above each layer lasted for about 20−25 years. This shows that it took about 20−25 years for a killed or stressed *Goniopora* coral reef to recover under favorable sea-level and SST conditions. However, the calibrated ^{14}C dates are not accurate enough to place a definitive constraint on this. More accurate dating of the *Goniopora* profile by the AMS ^{14}C method is required to clarify this matter.

5. Conclusions

Ecological, micro-structural and skeletal Sr/Ca data extracted from a ~ 3.42 m thick *Goniopora* profile in an emerged reef terrace in the northern South China sea consistently suggest that each of nine layers of *Goniopora* corals dated between 7.0 and 7.5 ka BP abruptly died during winter seasons. This represents the first documented evidence for high-latitude "cold-bleaching" and mortality of reef corals during the "Early−mid Holocene climatic optimum" in East Asia, possibly related to intensified winter monsoons, leading to over-cooling of SSTs to below 18 °C. Mass coral bleaching affecting thousands of square kilometres of coral reef has become an increasingly serious global environmental problem, with global warming being blamed as the main cause [11]. In this context, it is intriguing to note that high-latitude cold water bleaching occurred during both the Mid-Holocene (this study) and the present time [29], when the probability of warm-water bleaching is also high, implying more severe annual SST oscillations. Such a phenomenon should be taken into consideration among climate change projections for coral reefs.

In addition, the 3.42 m thick *Goniopora* profile also recorded a detailed sea-level path during 7.0−7.5 ka, with an average rate of sea-level rise of 6.6 ± 2.8 mm/year. However, morphological evidence shows the sea-level rise was not smooth, but punctuated by several short-lived hiccups or even reversals. Moreover, the calculated duration of growth hiatus for the whole reef profile indicates that it took about 20−25 years for seriously stressed or killed reef corals to recover.

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