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Coral reefs in the South China Sea: Their response to and records on past environmental changes

YU KeFu*

South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China

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This paper reviews both the recent and longer-term (Holocene) ecological history of coral reefs in the South China Sea (SCS). (1) Local ecological monitoring since the 1960s shows that the coral reefs in the South China Sea have declined dramatically, reflecting the rapid decrease of living coral cover and the great loss of symbiotic zooxanthellae. Collectively, this has led to a significant decrease of annual $CaCO_3$ production. Heavy anthropogenic activities and global warming are recognized as major triggers of the observed coral reef degradation. Observations show that the modern coral reefs in the SCS are a source of atmospheric CO_2 in summer. (2) Coral reefs of the SCS have been widely used to reveal longer-term environmental variations, including Holocene high-resolution sea surface temperature (SST) and abrupt climate events, millennial-scale El Niño variations, millennial- and centennial-scale sea level oscillations, strong and cyclic storm activities, East Asian monsoon intensities, variation in seawater pH, and recent seawater pollution. (3) Coral reefs of the southern SCS have experienced repeated episodes of bleaching over the last 200 years due to high SST and intense El Niño events; coral reefs of the northern SCS suffered high levels of mortality during several abrupt winter cold-water bleaching events during the middle Holocene warm period. On average, recovery after the middle Holocene cold-bleaching took 20–30 years; recovery following other middle Holocene environmental stresses took approximately 10–20 years. Such findings have significantly contributed to the understanding of the present ecological pressures faced by the coral reefs in the SCS, the histories of Holocene climate/environment changes, and the long-term models of coral reef responses to various past environmental changes.

coral reefs, ecology, environment, climate, Holocene, South China Sea

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Coral reefs, the most diverse and vulnerable ecosystems on Earth, provide a variety of valuable goods and services to humans [1, 2]. It is estimated that approximately 500 million people rely on coral reefs for food resources, recreation opportunities, coastal protections, and building materials [3]. However, perhaps most significantly, corals have proven to be excellent archives in recording environmental history of tropical oceans over the past hundreds of thousands years for the following reasons [4]: (1) they are sensitive to environmental changes; (2) they have a large yearly growth rate (up to 1–2 cm/yr); (3) their growth bands provide a clear annual chronology, much like tree rings; (4) they have long growth histories (e.g., 200–300 years, or up to 800 years); (5) they are widely distributed throughout tropical and temperate regions of the world's oceans; and (6) they are ideal for high-precision U-series dating (e.g., typical precision <1% at two σ error). As a result, coral-based high-resolution climate reconstructions have made significant contributions to the knowledge of global climate change over the past glacial-interglacial cycles. For example, a 420-year record of coral-based sea surface temperature (SST) and salinity

*Corresponding author (email: kefuyu@scsio.ac.cn)

reconstruction for the Great Barrier Reef suggests that the global Little Ice Age expansion might have been driven, in part, by greater polarward transport of water vapor from the tropical Pacific [5]. Coral records from the Pacific and Indian Oceans also strongly suggests that tropical oceans play an important role in driving global climate change [6].

Coral reefs are widely distributed across the South China Sea, covering the areas from Zenmuansha (~4° N) in the south, to Leizhou Peninsula, Weizhou Island (~20°–21°N), and Hengchun Peninsula (~24°N) in the north [7] (Figure 1). The coral reefs in the SCS are dominated by fringing reefs, platform reefs (with sand cays), and atolls. The developmental history of reefs in the SCS can be dated back to the early Miocene or late Oligocene [7]. Similar to other reefs across the planet, coral reefs in the SCS play a critical role in providing valuable goods and services to humans. Coral reefs in the SCS also show a great potential for understanding the mechanisms, processes, and ecological response(s) of past environmental changes and anomalous impact events.

1 The distribution and ecological status of the coral reefs in the SCS

Coral reefs in the SCS can be divided into the following nine geographical regions (Figure 1): South China coast and its offshore islands, Hainan Island and its offshore islands,

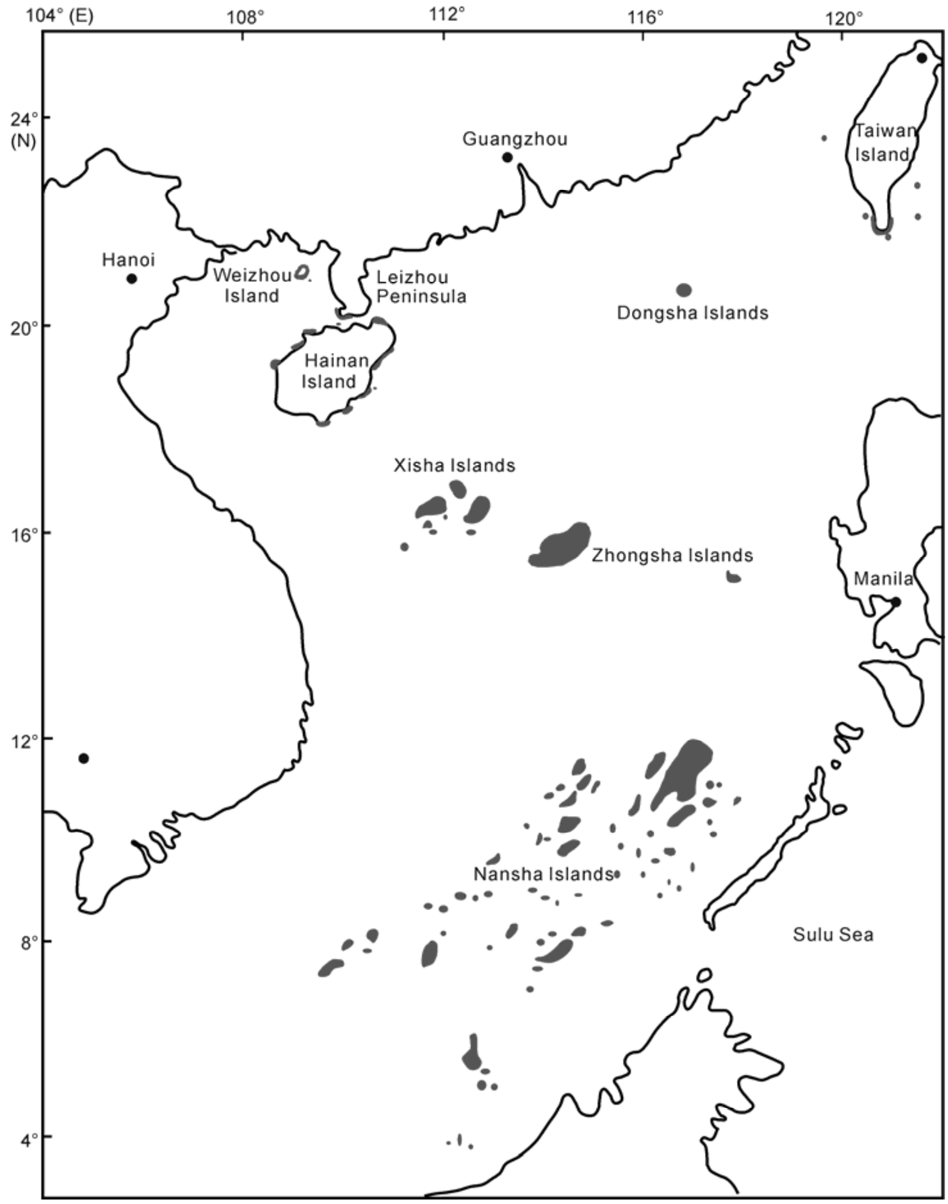

Figure 1 Coral reef distribution in the South China Sea (after ref. [7]). Coral reefs along Vietnamese and Philippine coasts and their offshore islands are not included in this figure due to a paucity of information.

Taiwan Island and its offshore islands, the Dongsha islands, Zhongsha Islands, Xisha Islands, Nansha Islands, the Vietnamese coast and its offshore islands, and the Philippine coast and its offshore islands. The coral reefs in the Dongsha, Zhongsha, Xisha and Nansha Islands are dominated by atolls, whereas the other five regions consist mainly of fringing reefs. It is estimated that the shallow-water (<50 m) modern coral reef area in the SCS (excluding coral reefs along the Vietnamese and Philippine coasts and their offshore islands) approximates 8000 km^2 [7]. The area of coral reef carbonate platforms in the SCS would be significantly larger than this because many Tertiary reef complexes or carbonate platforms have subsequently been identified outside the modern coral reef areas of the SCS [7].

Long-term monitoring suggests that the coral reefs of the SCS have suffered a dramatic decline over the past 50 years, reflected in the decrease of live coral cover (the most efficient proxy for indicating 'health' of coral reefs). Live coral cover in Daya Bay (northern SCS) declined from 76.6% to only 15.3% between 1983/1984 and 2008 [8]; Luhuitou fringing reef (Hainan Island, northern SCS) coral cover decreased from ~80%–90% to ~12% between 1960 and 2009 [9]; and that in Yongxing Island (the Xisha Islands, central SCS) decreased from 90% to ~10% between 1980 and 2008 [10–12]. Intense anthropogenic activities are commonly thought to be the main factor that has driven the observed declines. For example, Luhuitou fringing reef has successively experienced reef rock digging, destructive fishing, marine culturing, coastal constructing, and significant tourist diving activities since the 1960s [9]. Due to an increase in human activities, as well as global warming, coral reefs worldwide have also experienced severe declines recently. For example, live coral cover on the Great Barrier Reef (Australia) has decreased from ~50% to only ~20% from 1960 to 2003 [13], and the Caribbean live coral cover decreased from ~50% to just ~10% between 1977 and 2001 [14]. The long-term decline trends of the live coral cover in these areas are shown in Figure 2.

Coral reefs of the Nansha Islands (southern SCS) have experienced few direct anthropogenic impacts because of their remoteness and the political complexity, such that the live coral cover is higher than other regions in the SCS. For example, the live coral cover in Meiji Reef (the Nansha Islands) is estimated to be approximately 40% in 2007 (unpublished). However, a recent study [15] on the symbiotic zooxanthellae of corals in Meiji Reef indicated that the local corals lost 31%–90% of their symbiotic zooxanthellae in 2007, suggesting that the corals have experienced significant bleaching. On the basis of that observation, coral reefs of the Nansha Islands are not in pristine condition, despite their apparently 'healthy' status as reflected by the high live coral cover. Worldwide, only a few coral reefs remain unaffected by human activities [16] or global environmental changes. Unfortunately, this is not the case for coral reefs in the SCS.

The severe decline of coral reefs in the SCS has significantly affected their ecological functions and role in the carbon cycle. For example, the dramatic decline of Luhuitou fringing reef has resulted in the decrease of the $CaCO_3$ production by 80%–90% since 1960 [17]. It is estimated that the annual $CaCO_3$ production of the coral reef regions (excluding those along the Vietnamese and Philippine coasts) in the SCS is 2.14×10^{10} kg, which approximates to 1.6%–3.3% of global reefal carbonate production [7]. Again, this is only a minimal estimated value given the minimal estimation of the modern coral reef area in the SCS.

Although there is still a significant debate on the role (i.e., as a sink or a source) of coral reefs in global carbon cycle, it is widely accepted that the contribution of coral reefs to

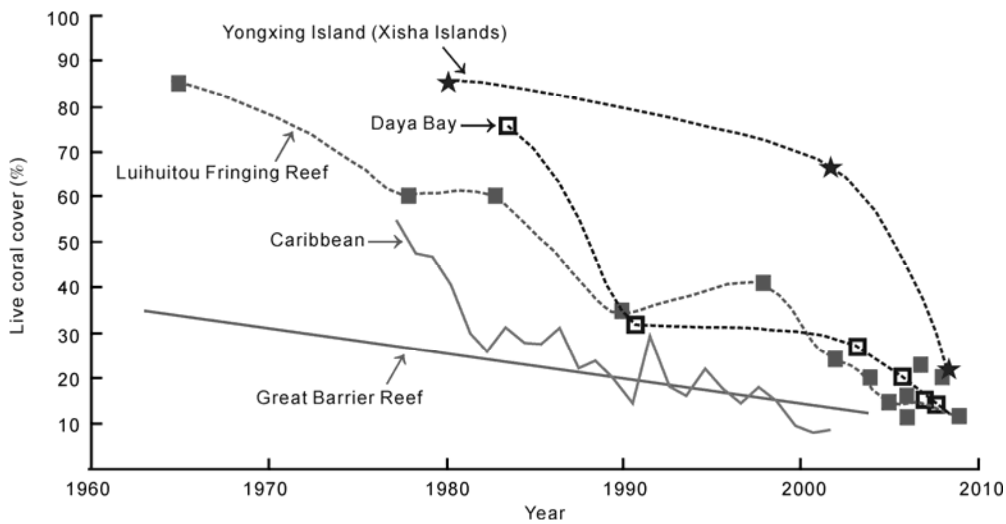

Figure 2 Live coral cover declines in the South China Sea in comparison to long-term trends in the Great Barrier Reef and the Caribbean (after refs. [8–14]).

atmospheric CO_2 is dependent largely on their topographic and oceanographic settings [18]. Reefs may act as a net source of CO_2 if they are dominated by corals, but may take up atmospheric CO_2 and act as a sink to the atmosphere if they are dominated by microalgae [19]. It is believed that coral reefs played a key role in driving the atmospheric CO_2 (~80 μmol/mol) increase during the retreat of the Wisconsinan glaciers ca. 14 ka [20]. Based on field measurements of air-sea CO_2 exchange in three coral reef areas of the South China Sea (i.e., the Yongshu Reef atoll of the Nansha Islands, southern SCS; Yongxing Island of the Xisha Islands, central SCS; and Luhuitou Fringing Reef of Hainan Island, northern SCS) during the summers of 2008 and 2009, Yan et al. [21] found that both air and surface seawater partial pressures of CO_2 (P_{CO_2}) showed regular diurnal cycles, with minimal values occurring in the evening and maximal values occurring in the morning. Although there exists differences spatially in air-sea CO_2 flux across the SCS, coral reefs of the SCS appear to be a net source of CO_2 to the atmosphere in summer.

Seawater acidification partially results from an increase of atmospheric CO_2, and is thought to reduce a reef coral's calcification ability. For example, coral calcification rates in the Great Barrier Reef have reduced by 14%–21% since the 1990s [22, 23]; which is unprecedented in at least the last 400 years. Shi et al. [24] studied the coral calcifications in the SCS, and divided the calcification rates of corals from the Meiji Reef in the southern SCS into five periods over last 200 years and identified the following trends: calcification increases in 1770–1830, 1870–1920, and 1980–2005; and decreases in 1830–1870 and 1920–1980, respectively. Over the past two centuries, the largest increase in coral calcification was 4.5%, occurring in 1770–1830; whereas the largest decline in coral calcification was 6.2%, occurring in 1920–1980. From 1980 to 2005, coral calcification in the SCS showed a slightly decreasing trend. Further analysis suggested that coral calcification in the SCS was not correlated with atmospheric CO_2 concentrations but closely related to the SST variations, which means that the rising atmospheric CO_2 has a negligible effect on the coral growth in the southern SCS, at least during the last century. Another study on coral calcification rates spanning from 1962 to 2007 in Daya Bay (northern SCS) suggested that corals in this relatively high latitude area benefited from seawater warming between 1962 and 1993 and showed increased calcification rates. However, local coral growth has been stressed by high SST since 1993, and accordingly, the calcification rate has been reducing gradually [25]. It seems there is a threshold between coral calcification and SST, when SST is lower than the threshold, corals can increase their calcification along with the seawater warming; and when SST is above the threshold, corals will reduce their calcification. The spatial difference of coral calcifications and their relationships with SST in Meiji Reef (southern SCS) and Daya Bay (northern SCS) is most likely the result of regional environmental differences.

2 Holocene environmental processes recorded by corals of the SCS

Reef corals are well-known as excellent archives for recording the environmental history of the tropical oceans because they are very sensitive to environmental changes and can accurately record environmental variations (such as SST, sea level, El Niño, seawater pH values, flooding, storms) in their aragonite skeletons. Subsequently, the widely distributed coral reefs in the SCS have been used to reveal Holocene variations of SST, the occurrence of short-term cooling events, oscillations of sea level and El Niño, frequency of past storm activities, seawater pH variation, and the history of East Asian monsoons.

2.1 SST fluctuating process and climate cooling events since the middle Holocene

The so far established relationships (formulas or equations) between coral geochemical proxies (e.g., Sr/Ca, Mg/Ca and δ^{18}O) and SST have been investigated for several coral reefs in the SCS, including the Nansha and Xisha Islands, Hainan Island, Leizhou Peninsula, and Taiwan Island [26–35]. Such studies allow for investigation of high-resolution reconstructions of past SST.

Based on seasonal to monthly-resolution Sr/Ca and δ^{18}O data of Holocene and modern *Porites* corals from Leizhou Peninsula (northern SCS), Yu et al. [4] investigated SST changes since the middle Holocene using the established Sr/Ca- and δ^{18}O-SST relationships. The results suggested a general decreasing trend in SST from ~6800 to 1500 years ago, despite showing shorter climatic cycles. Compared with the mean Sr/Ca-SST in the 1990s (24.8°C), the 10-year mean Sr/Ca-SSTs were 0.9 °C–0.5°C higher between 6.8 and 5.0 ka BP, then dropped to the present level by ~2.5 ka BP, and reached a low of 22.6°C (2.2°C lower) by ~1.5 ka BP (Figure 3(a)). Such a decline in SST was accompanied by a similar decrease in the amount of monsoon moisture in the SCS, resulting in a general decrease in the seawater δ^{18}O values (reflected by offsets of mean δ^{18}O of corals relative to that in the 1990s). In contrast with the general cooling trend of the monsoon climate in East Asia, SST increased dramatically in recent times, with that in the 1990s being 2.2ºC warmer than that ~1.5 ka ago. This is significant in that it suggests that recent anthropogenic-induced global warming may have reversed the natural climatic trend in East Asian monsoon regime [4].

The above SST variations revealed by the corals from Leizhou Peninsula have also been identified from other reef regions in the SCS. For example, Sr/Ca records of three middle Holocene corals from Sanya (Hainan Island, northern SCS) suggests that the winter SST was equivalent to

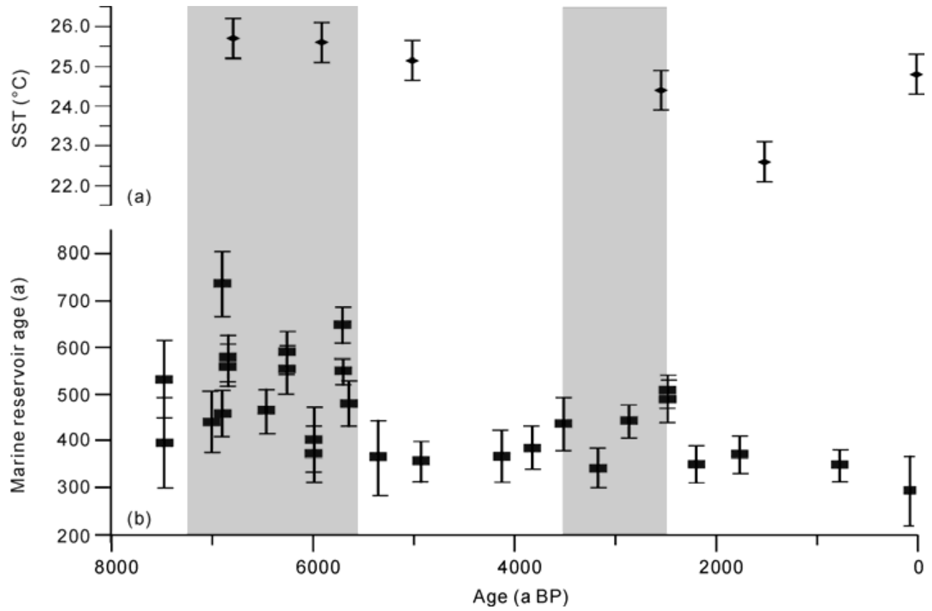

Figure 3 Coral records of SST process (a) (after ref. [4]) and marine reservoir ages (*R*) (b) (after ref. [35]) since the middle Holocene. Although the overall declining trend in carbon reservoir age from 7500 a BP to present suggests an intensification of El Niño activity, the two *R* plateaus at around ~7.5–5.6 and 3.5–2.5 ka BP indicate short periods of weaker of El Niño.

that of the present, whereas the summer SST over 6.5–6.1 ka BP was 1–2°C warmer than present [32]. Sr/Ca records of corals from the Xisha Islands (central SCS) suggested that the monthly summer SST from approximately 540 years ago was ~1°C lower than present, coinciding with the well-known "Little Ice Age" [28]. Growth rates [33] and Sr concentrations [34] of corals from the Xisha Islands have also been used to track SST variations over the last 100 to 220 years, with the results neatly correlating to the warming characteristics seen in instrumental SST. The above study reinforces the reliability of coral-based SST reconstructions in the SCS.

The higher-than-present summer SST over 6.8–5.0 ka BP indicates that it was a period of intense East Asian summer monsoon [4, 32]. However, before 6.8 ka BP, coral records from the northern SCS suggested that the East Asian winter monsoon was stronger than present. A detailed ecological, micro-structural and skeletal Sr/Ca study [27, 36] of a 3.42 m thick *Goniopora* reef profile (which has an area >1 km^2 and dominated by branchy *Goniopora* corals with a spatial coverage of >90%, from an emerged Holocene reef terrace at Leizhou Peninsula, northern SCS) revealed that the summer SST during 7.5–7.0 ka BP was comparable to those in the 1990s, while the winter SST was about 2–3°C lower than present, suggesting a stronger winter monsoonal activity. Although the Sr/Ca-SST and the uniquely developed *Goniopora* reef (i.e., large area and high spatial coverage) clearly indicate that climatic conditions for reefal establishment were optimal for coral growth, cyclic occurrences of growth hiatus in the reef profile suggests that a series of abrupt climatic events occurred during subsequent reefal development. Further analysis on coral skeletal Sr/Ca data and density bands suggested that it was high-frequency and large-amplitude (>7°C) winter cooling that resulted in the cyclic mass coral mortality and the forming of the hiatuses. Such events are named "Leizhou events", characterized by abrupt, high-frequency and large-amplitude cooling during the Holocene warm period. Leizhou events clearly indicate that the middle Holocene warm period was unstable.

2.2 Millennial-scale fluctuations of El Niño activities since the middle Holocene

El Niño has numerous effects on the SCS, with one being the seawater ^{14}C concentrations. During the El Niño years, ^{14}C in southeastern Pacific waters increases due to significantly reduced upwelling, reduced westward transport, and the northward shift of Northern Equator Current (NEC) partially supplied by waters from the Pacific Equatorial Divergence [35]. Collectively, this leads to a higher ^{14}C content and a lower marine reservoir age (*R*) for the NEC, and consequently, for the seawater entering into SCS driven by NEC [35]. During the normal or La Niña years, upwelling in the southeastern Pacific is active, westward transport of these waters is enhanced due to strong easterly winds, which together result in relatively depleted-^{14}C or high *R* waters in the NEC, and consequently, for the SCS.

On the basis of the established relationship, Yu et al. [35] examined seawater ^{14}C related *R* variations during the Holocene using paired measurements of Accelerator mass spectrometry (AMS) ^{14}C and thermal ionization mass spectrometry (TIMS) ^{230}Th on 20 pristine corals. The results (Figure 3(b)) showed large fluctuations in *R* values over the past 7500 years with two distinct plateaus during 7.5–5.6 and 3.5

–2.5 ka BP, roughly reflecting millennial-scale fluctuations. The results provide the first database for Holocene *R* values of the SCS and will be critical for improving radiocarbon calibration of marine samples. The two *R* plateaus were interpreted as being related to two intervals with weakened El Niño – Southern Oscillation (ENSO) and intensified East Asian summer monsoon. The overall decreasing trend in *R* values from 7500 a BP to present suggests a long-term strengthening of El Niño activity or/and the weakening of the East Asian summer monsoon intensity.

A weakened ENSO over the middle Holocene was also recorded in corals from Hainan Island. For example, spectral analysis of Sr/Ca-SST from three corals dated at 6.5–6.1 ka BP in Hainan Island suggested that the ENSO cycles (i.e., 2.5–7 years on average) were much weaker in the middle Holocene than at present, suggesting that the ENSO variability was suppressed by the intensified East Asian summer monsoons [32]. The more recent, but stronger, El Niño activity was recorded in both $\delta^{18}O$ and $\delta^{13}C$ proxies of a modern coral covering 1951–1999 from the Nansha Islands. Those data suggest that since 1972, the climate in the El Niño years was becoming warmer and wetter in the southern SCS. The coral proxy data also match particularly well with instrumental climate records from the neighboring Taiping Island [29, 37]. Such studies reinforce the significance of SCS corals in understanding the history of significant climatic changes and variability, such as ENSO.

2.3 Coral records of Holocene millennial-, centennial- and decadal-scale sea level oscillations

Because of the close relationship between coral growth and sea-level variations, coral reefs within tectonically stable areas are excellent archives of past sea-level status and process [38, 39]. For example, because *in situ* massive corals can only develop below low spring tide, they therefore reflect the minimal sea level. Microatolls on intertidal reef flats are circular coral colonies with a flat-topped, dead core surrounded by a living rim. Because the prolonged sub-aerial exposure at low tide kills the coral's upper surface as it grows vertically and thus constrains its subsequent growth to the horizontal plane, coral reefs have great potential as sea-level proxies. Accordingly, the absolute elevation of the upper rim of live coral tissue is determined by the relative durations of submersion and sub-aerial exposure, which are in turn strongly linked to sea level. Because of this precise relationship between low tide level and coral rim height, the topographies of microatolls have been considered as natural tide gauges for the past tens to hundred years and have been successfully used to detect annual-scale sea level fluctuations [40]. Together with the great advantages in high-precision dating, coral reefs play very important roles in reconstructing past sea level changes.

Using the relationship between coral growth and sea levels, Zhao and Yu [41] employed detailed elevation surveying, density sampling, and high-precision dating on the *in situ* massive corals developed in Leizhou Peninsula (northern SCS). Eighty high-precision thermal ionization mass spectrometric ^{230}Th ages for 57 *in situ* massive *Porites* and *Favia* coral (microatoll) colonies show that six coral reef developmental stages can be clearly identified as: 7100–6500, 6285–5676, ~5000, 4156–3675, 2891–2321, and ~1500 a BP, roughly over millennial-scale cycles. Spatially, the 7100–6500 a BP corals occur within the central part of the reef flat, whereas the progressively younger corals are distributed on the flanks of the reef flat, reflecting lateral reef accretion to both sea and present beach directions. The elevations of these dated corals are about 148 to 219 cm above the modern microatoll surfaces. Together with their zonal distribution pattern, those data suggest that the sea level above coral development stages was at least 148 to 219 cm higher than at present, with the highest sea-level occurring at 7100–6500 a BP. Sea level has then lowered progressively since the middle Holocene [27, 41–48] (Figure 4(a)).

During each episode of the abovementioned millennial-scale sea-level highstands, sea level was not stable and further oscillated on centennial scales. For example, at least four cycles of fluctuations during 7050–6920, 6920–6820, 6820–6690, 6690–? a BP were recorded by microatolls. The amplitude of these centennial-scale fluctuations was about 20–40 cm [42] (Figure 4(b)). Such centennial-scale sea level oscillations were also recorded in a late Holocene palaeo-beach profile, which indicated a short-term drop in the sea level at ~1.5 ka BP, while the sea level was overall higher than at present during 1.7 to 1.2 ka BP [43].

Multiple decadal-scale sea-level falls were recorded from *in situ* reef coral profiles. For instance, a detailed study of a well-developed *Goniopora* reef profile from this Leizhou Peninsula reef shows that general sea level rise during 7500–7000 a BP was punctuated by multi-decadal lowering events, which resulted in the emergence and erosion of *Goniopora* corals [27].

These indicators from Leizhou Peninsula suggested that the sea level was similar in height to the present level at ~7300 a BP. It exceeded the present level by at least ~1.8 m at ~7000 a BP, and was 128 cm higher-than-present at 1.2 ka BP. During the last 1200 years, the coastline has retreated by 210 m as sea levels have fallen [27, 43]. Such sea level variations are also recorded by corals developed at Sanya (southern Hainan Island) [44], Qionghai (northern Hainan Island) [45], and along the Vietnamese coast, western SCS [46].

2.4 Coral reef records of intense storm history over last 4000 years in the southern SCS

Extreme events such as tropical storms, cyclones, and tsunamis have a severe impact on human populations and economy, and play an important role in coral reef develop-

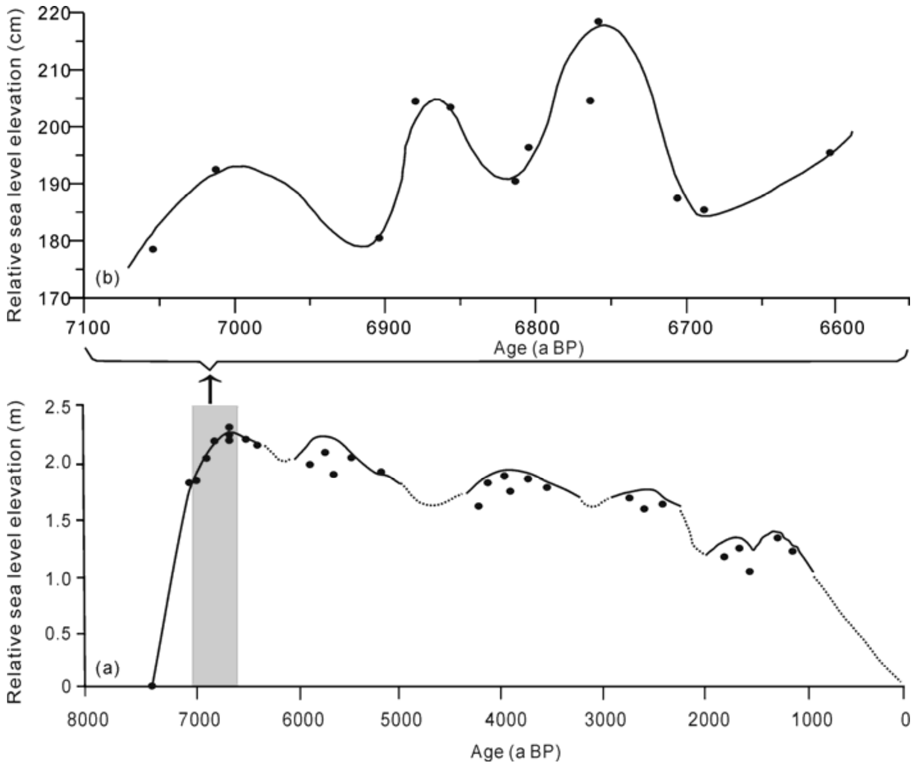

Figure 4 Holocene millennial-scale (a) and centennial-scale (b) sea level oscillations recorded in coral reefs of Leizhou Peninsula (northern SCS) (after refs. [27, 41–48]).

ment and biodiversity. The economic loss from extreme climatic events over the last decade has surged by 10 times relative to that of the 1950s [49]. The most recent IPCC Report [50] predicted that there will be a likely increase in the intensity and frequency of tropical cyclones in the future. If and how global warming affects cyclonic activity is a topic of considerable interest. Assessing anthropogenic effects on variations of cyclones requires decoupling recent and future trends from longer-term periodicities/variability, as well as a better knowledge of cyclone occurrences over the past millennium. The available instrumental/historical record, however, is far too short to document and understand the complex links within the climate system responsible for cyclones. Thus, there is an urgent need to extend the records beyond the instrumental measurements by geological data so that we may capture the full range of natural variability inherent to the climate system.

After detailed investigations of storm-transported coral blocks scattered on the reef flat of the Yongshu Reef (southern SCS), Yu et al. [51] suggested that the surface ages of well-preserved uplifted corals could indicate the ages of past storm occurrences. This inference is supported by modern observations; for example, a massive *Porites* with a >2 m diameterz was transported (and killed) by the Indian Ocean tsunami in Thailand on 26 December 2004 (www.planetsave.com/ps_mambo/index.php?option); and some coral blocks up to 3 m in diameter were tossed onto the reef flat when Cyclone Fay passed Scott Reef (northwestern Australia) on 21st March 2004 [52]. All such corals were still alive at the time of wave transportation, but then died after relocation and/or exposure. Using the TIMS U-series dating method, Yu et al. [51] produced high-precision ages of large storm-transported corals on the Yongshu Reef and identified six strong storms occurred during the last millennium with an average of 160-year cycle. The work is also supported by an additional study on the sedimentation rate and grain size of lagoon column sediments from the same reef [49, 53].

A 15.4-m-long sediment core was vibrated from the lagoon of the Yongshu Reef by Yu et al. [53]. Then the age profile of this column was established by high-precision dating of 26 well-preserved coral branches. Each date is in correct stratigraphical sequence, with the smallest sampling interval being only 13 cm and thus, provides the best chronology so far reported for lagoon column sediments. The results indicate that the deposition rate varied in the range of 0.8 and 24.6 mm/a, with an average of 3.85 mm/a. Two periods of rapid deposition, one from 103 to 305 AD and the other for the last 1000 years, were interpreted to be the results of intensified storm activities. Episodes of elevated deposition within the last 1000 years are temporally correlated with strong storm events identified by U-series dates of storm-relocated coral blocks in the area [51].

Grain size analysis [49] of this 15.4-m-long core suggested that: 1) Over last 4000 years there were at least 20 strong storm/tsunami events, with 13 so far identified within the last 1000 years (Figure 5). The data also suggest three extremely stormy periods centering around 1200 AD, 400 BC and 1200 BC, respectively. 2) There is an overall increasing trend in the intensity of sedimentary dynamics (or storm activities) over the last 4000 years, but this trend is not obvious within the last millennium. 3) Spectral analysis of the coarse-fraction contents yields 18.7, 23.6, 25, 27, 32, 54, 65, 132, and 195-year cycles, which correlate well with solar activities, suggestive of solar activity forcing on storm occurrences in the southern SCS.

Overall, the combination of wave-transported coral blocks, and coarse-fraction contents and sedimentation rates of the lagoon sediments, can provide excellent and comprehensive records of past intense storm/tsunami activity in tropical oceans.

2.5 Coral records of seawater pH values since the middle Holocene in the southern SCS

Liu et al. [54] used positive thermal ionization mass spectrometry to generate high precision δ^{11}B values of the middle late Holocene corals from the SCS, and then converted the δ^{11}B values into pH data based on the statistical relationship between them. The results indicated that the pH values in the SCS showed a gradual increase from the middle Holocene warm period (~7 ka ago) until ~1.2 ka BP, followed by a sharp decrease to approximate modern low pH values. Low pH values that are equivalent to, or even lower than, the modern values were observed for the time period around 6 ka ago when both SST and sea level were higher than at present. Liu et al. [54] suggested that the modern low pH values were a result of the large amount of emissions of anthropogenic CO_2 since the Industrial Revolution. Conversely, it is likely that the similar pH values at ~6 ka BP were driven by strong summer monsoons that intensified upwelling and brought more deep water with low pH values to the SCS surface [54]. The study implies that the impact of anthropogenic atmospheric CO_2 emissions may have reversed the natural pH trend in the SCS since the middle Holocene.

2.6 Coral records of the East Asian monsoon in the SCS

The weather and climate of China is closely related to the activities of East Asian monsoons, therefore it has long been a focus to find East Asian monsoon information from corals in the SCS.

Yu et al. [29] analyzed the relationship between winter δ^{18}O of coral YSL-12 from the Yongshu Reef (the Nansha Islands) and the WMI (East Asian winter monsoon indices) from 1953 to 1997, and found they were well positively correlated (n=45, r=0.42, p<0.01). The low winter coral δ^{18}O or the high SST in the Yongshu Reef sea area suggests a weak East Asian monsoon. Conversely, the high coral δ^{18}O or the low SST suggests a strong East Asian monsoon. Such relation of coral δ^{18}O on the intensity of East Asian monsoon is crucial for understanding the high resolution climate history of palaeo-monsoons in East Asia. Skeletal δ^{18}O of corals from Hainan Island was also found to be tightly correlated to the East Asian winter monsoon intensity [55–57]. For example, a coral dated to ~4400 a BP from Hainan Island indicated that the winter monsoon was stronger than at present, and which induced low SST, strong evaporation, and the enrichment of δ^{18}O in the coral skeleton [58]. Based on the relationship between winter SST and East Asian winter monsoon intensity, coral Sr/Ca ratios (an SST proxy) from Hainan Island suggested a decline of East Asian winter monsoon intensity from 1905 to 1996 [59].

Corals from the SCS also provide information on variations of the East Asian summer monsoon. For example, summer SST determined from the middle to late-Holocene corals from Leizhou Peninsula (northern SCS) demonstrated a long-term decline since 7000 a BP. This interpretation is consistent with the general weakening of the East Asian summer monsoon since the early Holocene, mostly likely in response to a continuous decline of solar radiation [4]. Profiles of radiocarbon marine reservoir ages calculated from paired measurements of AMS ^{14}C and TIMS ^{230}Th of corals from the SCS also suggested an overall decline of East Asian summer monsoon intensity over the last 7500 years [35]. Strong East Asian summer monsoons identified in middle Holocene corals from Hainan Island are thought to

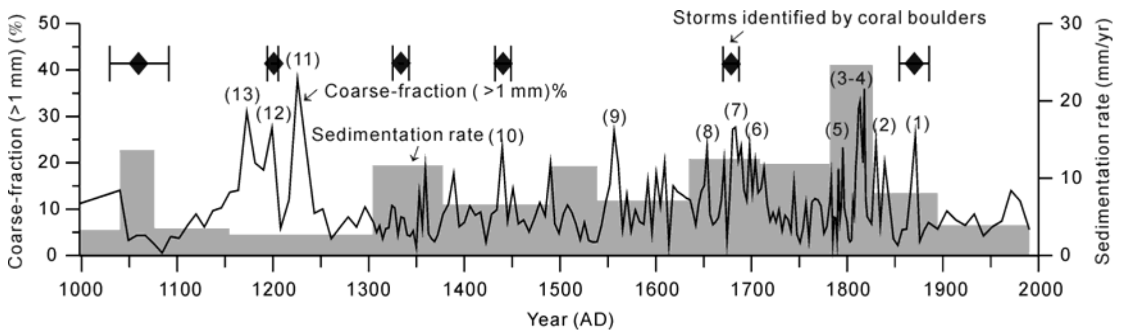

Figure 5 Coral reef records of strong storm occurrences over the last 1000 years in the southern SCS (after refs. [49, 51, 53]).

have suppressed the activities of El Niño during that period [32].

2.7 Coral records of other environmental information in the SCS

As reef corals are very sensitive to subtle changes of environmental conditions, they are widely used in the monitoring of seawater quality, including sewage discharging and heavy metal pollution. For example, a study of Pb and Cd concentrations in coral skeletons indicated that they could accurately trace the process of industrialization [60]. In Daya Bay, northern SCS, annual variations of heavy metals in corals revealed that between 1976–2007 AD, two years (1979 and 1991) exhibited markedly elevated levels of metal concentrations, suggesting extreme episodes of local pollution [61]. Studies [62–64] on Fe/Ca, Mn/Ca, Zn/Ca, P/Ca and Ba/Ca of corals (covering 1976–2007 AD) also from Daya Bay suggested that they are all ideal proxies of seawater environmental changes. Both Fe/Ca and Mn/Ca recorded the impact on the seawater from heavy terrestrial sediment input driven by construction processes of the nearby nuclear power stations; Zn/Ca recorded the sewage increase along with the industrialization; P/Ca recorded seawater phosphate concentrations and the associated phytoplankton dynamics in the eutrophic environment; and Ba/Ca recorded the stress of low temperature on the corals living in the relatively high-latitude bay. Indoor experimental studies [65, 66] suggested that the rapid increase of heavy metals such as Cu and Zn would have vital effects on corals by reducing their symbiotic zooxanthellae, lowering their photosynthesis, and eventually killing the corals.

Rare earth element (REE) concentrations of corals from the estuarine zones off the Wanquan River and the Pearl River suggested that they are significantly negatively correlated with regional sea-level rise [67]. Such REE features are proposed to be the result of seawater intrusion into the estuaries in response to contemporary sea-level rise. When sea level rapidly rises in the SCS, intrusive ocean saline seawater, characterized with low REE contents and enrichment of heavy REE, can dilute the REE levels and change their signatures at the estuarine zone waters. In this case, REE concentrations of coastal corals are indicators of sea level changes if the sites are not influenced by anthropogenic development. Coral skeletal δ^{13}C from the Nansha Islands may indicate annual variations of sunshine duration, total cloud cast, and rainfall of the coral growth site [37].

3 Coral reefs' response to historical climate change in the SCS

It is an indisputable fact that global coral reefs are an ecosystem that has experienced several recent significant declines. For example, by the year 2008, only ~46% of Earth's coral reefs were considered to be in a relatively healthy status [3]. Coral reef bleaching, characterized by expulsion of the symbiotic zooxanthellae, loss of algal pigmentation or both, is well known as the most important factor resulting in the degradation [68]. Although many factors can result in coral reef bleaching, higher SST and stronger El Niño have been accepted as the primary causes of large-scale coral reef bleaching events [69]. For example, the extremely high SST in the 1998 El Niño year resulted in 16% of global coral reef degradation. It impacted on almost all coral reef sites around the world, especially on the Great Barrier Reef (GBR) where several well-established and mature coral colonies (up to ~1000 years old) suffered mortality [70]. Some scientists predicted that coral reefs will be the first ecosystems to succumb to global climate change if current climate warming follows the predictions of 1–3 °C average increase in tropical sea surface temperatures by 2100 [70]. However, strong evidence from corals suggested that the tropical SST in the middle Holocene was 1–2 °C higher than the present [4, 71]. Corals did not suffer elevated mortality during that warmer-than-present temperature and have been continuously building reefs till today, suggesting that they have the ability to adapt high temperatures. In this case, studying how corals responded to historical temperature extremes in the past will greatly help the understanding of the present coral reef bleaching worldwide. Studies [27, 72] on the SCS corals did provide evidence that the past occurrences of coral bleaching have resulted from both high and low SSTs.

3.1 High SST induced coral reef bleaching in the southern SCS over the last 200 years

Mass coral reef bleaching episodes that result in large-scale coral mortality were first recorded in the early 1980s [73]. Prior to that, reports of coral bleaching were scattered or almost nonexistent in the literature [74]. To find proxies for past coral bleaching, a series of studies have investigated including symbiotic zooxanthallae density and the tolerance to temperature extremes of corals within the SCS. Investigations on the symbiotic zooxanthellae population density of corals in the SCS found that the symbiotic zooxanthella density displays significant interspecies variability, with branch corals usually having relatively less zooxanthella than massive species [75]. The zooxanthellae density difference from forms of coral species might partially explain why branching corals are more vulnerable to bleaching than massive corals [75]. Experimental studies have further confirmed that massive corals have a much stronger thermal tolerance than branching corals, and are among the most resilient species towards bleaching and other environmental stresses [76, 77]. In this case, massive *Porites* corals may potentially serve as sentinel species, where mortality is an indicator of severe historical ecological or environmental events, such as severe bleaching [78].

The past coral bleaching indicators, i.e., dead, massive *Porites* corals with diameter 1–2.5 m, are widespread in the Nansha islands, southern SCS. Yu et al. [72] collected 27 samples from well-preserved massive corals from two reefs (the Yongshu Reef and Meiji Reef) and dated their mortality ages (the ages of the most outside layers of the dead corals) with the high-precision (±1–2 years) U-series method. The results showed that the death of the all 27 corals occurred within last 200 years, correlating in time with historic El Niño events (Figure 6). After analyzing all possible reasons causing coral mortality, such as freshwater input, climatic cooling, low tide exposure, storm disturbances, volcanic eruptions, increased feeding from natural predators, outbreak of diseases, and human destructions, Yu et al. [72] considered that the episodic coral mortality of the Yongshu and Meiji Reefs was most likely caused by high temperature and radiation-induced bleaching during the El Niño years. Therefore, coral reef bleaching has repeatedly occurred at least over the last 200 years in the southern SCS, and is not a new phenomenon produced by more recent global warming.

3.2 Low SST induced cold-bleaching in the northern SCS over the middle Holocene warm period

Cold-bleaching, as the term implies, indicates coral bleaching as a result of cool temperatures. Heron Island in the southern Great Barrier Reef was the first reef site recognized to have experienced large area cold-bleaching in modern times (July 2003) [79], which is a very unusual ecological phenomenon in during the modern warm period when most coral reefs over the world are suffering from thermal stress. However, evidence from a coral reefs in Leizhou Peninsula, northern SCS, indicates that such large-scale cold-bleaching periodically occurred over the middle Holocene warm period [27].

The *Goniopora* profile [27] mentioned in section 2.1 developed in Leizhou Peninsula over the interval of 7.5–7.0 ka BP, is made up of at least 9 layers of *Goniopora*-dominated corals, and in each layer having coral cover >90%. The smoothed discontinuities between individual *Goniopora* layers reflect abrupt cooling events that resulted in mass mortality of the flourishing *Goniopora* over very short intervals, leading to the formation of clearly defined hiatuses. Analysis on skeletal Sr/Ca (a SST proxy) and density bands of those *Goniopora* corals suggested that the mass coral mortality and the formation of the hiatuses were the results of high-frequency and large-amplitude (>7°C) winter cooling. Sr/Ca-SST also indicated that minimal SSTs threshold for coral mortality was likely to be less than 10.7 °C. Considering the relationship between modern coral bleaching and coral mortality, i.e., only severe bleaching will result in mass coral mortality, Yu et al. [27] suggested that the mass mortality of the *Goniopora* corals over the middle Holocene warm period could be an unusual type of bleaching. Unlike the present coral bleaching which is induced by high SST, the middle Holocene *Goniopora* coral bleaching most likely resulted from winter cooling, thus, implying cold water bleaching. This was the first prehistoric evidence for cold-bleaching of reef corals at higher latitudes and added a new dimension to the understanding of coral bleaching. The results also showed that it took approximately 20–25 years for a bleached *Goniopora* coral reef to recover. Those inferences greatly help understand the present global bleaching phenomena and subsequent recovery processes.

Similar, but less intensive, cooling occurred in Southern China, including Daya Bay, northern SCS, in early 2008 (13th January–13th February). During the cold event, the lowest air temperature in Daya Bay area reached only

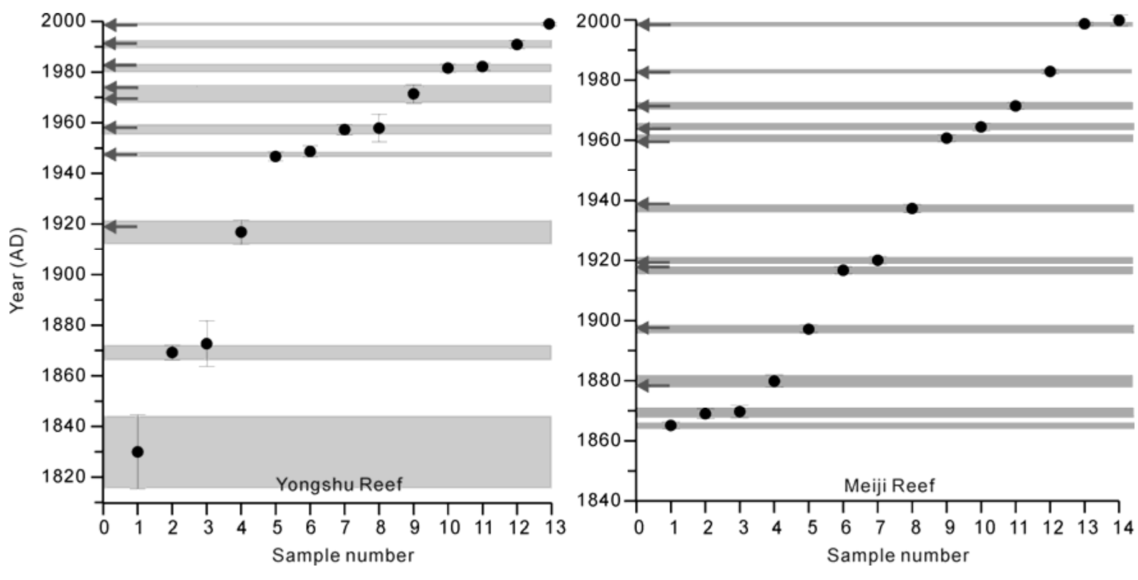

Figure 6 High SST induced coral reef bleaching in the Nansha Islands (southern SCS) over last 200 years (after ref. [72]).

6.6°C, and the mean SST for February fell to <14°C, with six continuous days at 12.3°C. Surprisingly, coral community surveys, conducted both before (August 2007) and after (late February 2008) the extreme 2008 cold event, demonstrated that the Daya Bay coral ecosystems were barely impacted upon during the cold period [8]. Those observations suggested that the SST at 12.3°C SST was still not low enough to result in coral cold-bleaching and mortality. In this case, the conclusion is supported that larger amplitude cooling (such as 10.7°C as Sr/Ca implied) during the middle Holocene warm period resulted in large area of *Goniopora* coral bleaching and mortality.

3.3 Massive coral mortality and recovery in SCS over the middle Holocene warm period

Information on environmental-induced historical coral mortality and recovery over the middle Holocene warm period is especially important given the current indications of global warming resulting in high-frequency coral reef bleaching and global coral reef decline. For this reason, Yu et al. [78] dated three middle Holocene corals that showed clear visual evidence of mortality and recruitment to understand their mortality and recovery, and used Sr/Ca and Mg/Ca measurements to explore seasons of their mortality and recovery. Multiple dates below and above the growth hiatuses suggest that the durations of growth hiatuses for SYO-13 (with mortality age of 6298±11 a BP) and SYO-28 (with mortality age of 6929±19 a BP) are 41±25 and 31±39 years, respectively, implying a rapid growth recovery after the mortality events (Figure 7). The third coral has a well-preserved mortality surface but lacks a subsequent recruitment. The Sr/Ca and Mg/Ca profiles indicated that the three corals died in different seasons (from spring to autumn), and the mortality appears to be unrelated to anomalous high SST-induced bleaching, although the summer SST (~31–32°C) was higher than that at present (~30°C), which seems to suggest that corals of the middle Holocene warm period had some adaptive ability to thermal extremes.

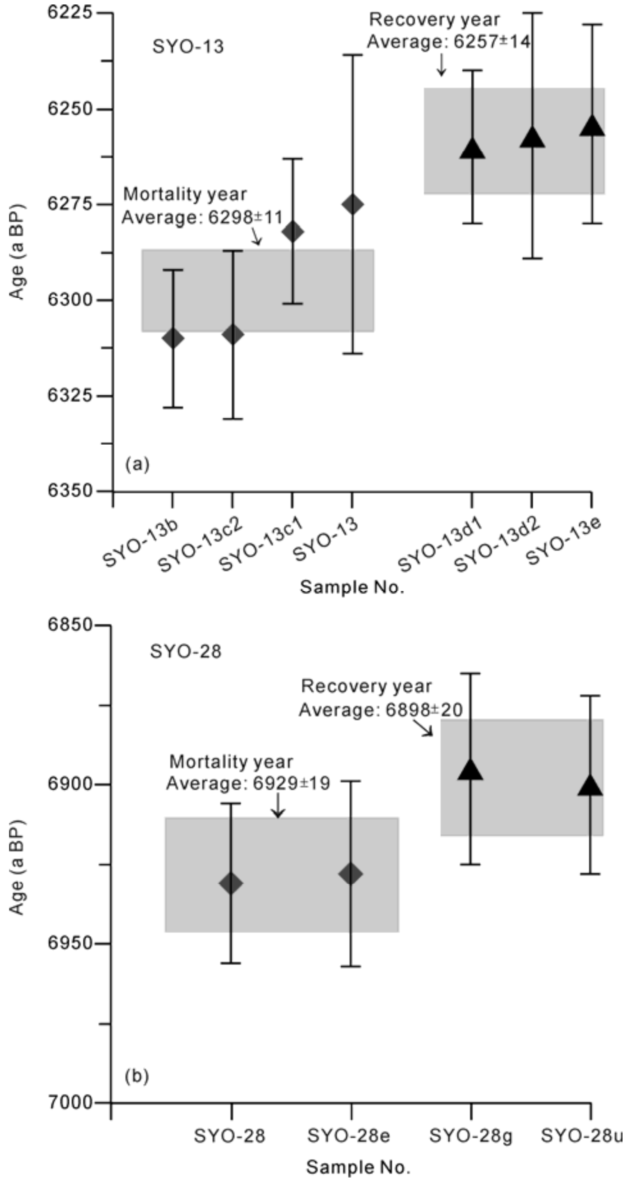

Figure 7 Mortality/recovery ages of two corals during the middle Holocene warm period (after ref. [78]).

4 Summary

(1) Coral reefs are widespread in the South China Sea, but have declined dramatically over last 50 years, reflected in the rapid decrease of living coral cover, an extensive loss of symbiotic zooxanthellae, and the lowering of annual $CaCO_3$ production. Heavy anthropogenic activities and global climate warming have had numerous detrimental impacts on the region's coral reefs. Present coral reefs in the SCS are playing as a source of atmospheric CO_2 in summer.

(2) As reliable proxies of marine environmental changes, Holocene coral reefs in the SCS provide high-resolution evidence for variation in SST and abrupt climatic changes, millennial-scale El Niño activity variations, millennial- and centennial-scale sea level oscillations, strong and cyclic storm activities, East Asian monsoon intensities, and seawater acidification. They have also been successfully used to monitor the historic seawater pollution.

(3) Both field observation and experiment study indicate that massive corals are the most resistant to environmental extremes because they have a greater density of symbiotic zooxanthellae than other corals species, such as branching corals. Using the mortality of massive corals as an indicator of severe historical ecological or environmental events, studies suggests that coral reefs in the southern SCS have experienced numerous episodes of bleaching over the last 200 years as a result of high SST and strong El Niño events. Coral reefs in the northern SCS experienced at least nine

cold-bleaching events during the middle Holocene warm period, most commonly during periods of abrupt winter cooling. On average, corals took 20–30 years to recover following each respective middle Holocene cold-bleaching event, and 10–20 years for recovery after mortality caused from other environmental stresses.

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