Available online at www.sciencedirect.com

SCIENCE DIRECT®

Global and Planetary Change 47 (2005) 301–316

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Mid–late Holocene monsoon climate retrieved from seasonal Sr/Ca and δ^{18}O records of *Porites lutea* corals at Leizhou Peninsula, northern coast of South China Sea

Ke-Fu Yu[a,b,c,*], Jian-Xin Zhao[b,d,*], Gang-Jian Wei[d,1], Xin-Rong Cheng[b,2], Pin-Xian Wang[b,2]

[a]South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
[b]Advanced Centre for Queensland University Isotope Research Excellence (ACQUIRE), The University of Queensland, Qld 4072, Australia
[c]Laboratory of Mar. Geol., Tongji University, Shanghai 200092, China
[d]Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

Received 25 February 2004; accepted 29 October 2004

Abstract

South China Sea (SCS) is a major moisture source region, providing summer monsoon rainfall throughout Mainland China, which accounts for more than 80% total precipitation in the region. We report seasonal to monthly resolution Sr/Ca and δ^{18}O data for five Holocene and one modern *Porites* corals, each covering a growth history of 9–13 years. The results reveal a general decreasing trend in sea surface temperature (SST) in the SCS from ~6800 to 1500 years ago, despite shorter climatic cycles. Compared with the mean Sr/Ca–SST in the 1990s (24.8 °C), 10-year mean Sr/Ca–SSTs were 0.9–0.5 °C higher between 6.8 and 5.0 thousand years before present (ky BP), dropped to the present level by ~2.5 ky BP, and reached a low of 22.6 °C (2.2 °C lower) by ~1.5 ky BP. The summer Sr/Ca–SST maxima, which are more reliable due to faster summer-time growth rates and higher sampling resolution, follow the same trend, i.e. being 1–2 °C higher between 6.8 and 5.0 ky BP, dropping to the present level by ~2.5 ky BP, and reaching a low of 28.7 °C (0.7 °C lower) by ~1.5 ky BP. Such a decline in SST is accompanied by a similar decrease in the amount of monsoon moisture transported out of South China Sea, resulting in a general decrease in the seawater δ^{18}O values, reflected by offsets of mean δ^{18}O relative to that in the 1990s. This observation is consistent with general weakening of the East Asian summer monsoon since early Holocene, in response to a continuous decline in solar radiation, which was also found in pollen, lake-level and loess/paleosol records throughout Mainland China. The climatic conditions ~2.5 and ~1.5 ky ago were also recorded in Chinese history. In contrast with the general cooling trend of the monsoon climate in East Asia, SST increased dramatically in recent time, with that in the 1990s being 2.2 °C warmer than that

* Corresponding authors. Advanced Centre for Queensland University Isotope Research Excellence (ACQUIRE), The University of Queensland, Qld 4072, Australia. Tel.: +61 7 33469753; fax: +61 7 33658530.

E-mail addresses: kyu@earth.uq.edu.au (K.-F. Yu), j.zhao@uq.edu.au (J.-X. Zhao), gjwei@gig.ac.cn (G.-J. Wei), xrchengk@online.sh.cn (X.-R. Cheng), pxwang@online.sh.cn (P.-X. Wang).

[1] Tel.: +86 20 85290093.

[2] Tel.: +86 21 65983207.

doi:10.1016/j.gloplacha.2004.10.018

~1.5 ky ago. This clearly indicates that the increase in the concentration of anthropogenic greenhouse gases played a dominant role in recent global warming, which reversed the natural climatic trend in East Asian monsoon regime.

Keywords: Holocene; SST; East Asian monsoon; coral δ^{18}O and Sr/Ca; South China Sea; global warming

1. Introduction

High-resolution Holocene climate reconstruction has been the focus of recent paleoclimate research, for it provides insight into the present climate condition and future climatic trend. Among numerous materials, reef corals have proved to be excellent archives of environmental history of tropical oceans over the past hundreds of thousands of years for the following reasons: (1) they are sensitive to environmental changes; (2) they have a large yearly growth rate (up to 1–2 cm/year); (3) their growth bands provide a clear annual chronology, much like tree rings; (4) they have long growth histories (e.g. 200–500 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. As a result, coral-based high-resolution climate reconstructions have made significant contributions to our knowledge of global climate change over the past glacial–interglacial cycle (Beck et al., 1997; Correge et al., 2000; Gagan et al., 1998). The combination of coral δ^{18}O and Sr/Ca can determine not only past sea surface temperature (SST) but also salinity and precipitation. For instance, McCulloch et al. (1994) first used combined coral δ^{18}O and Sr/Ca records to study the influence of 1982–1983 El Niño on SST and salinity in the Great Barrier Reef. Gagan et al. (1998) reconstructed the SST and surface-ocean water balance at 5350 years BP in the Great Barrier Reef and concluded that the sea surface water was 1 °C warmer and enriched in ^{18}O by ~0.5‰ relative to modern seawater there. Hendy et al. (2002) reconstructed SST and salinity of the past 420 years for the Great Barrier Reef and suggested that the global Little Ice Age expansion might have been driven in part by greater poleward transport of water vapor from the tropical Pacific.

In this paper, we use coral skeletal Sr/Ca and δ^{18}O records of five mid–late Holocene and one modern *Porites* corals from Leizhou Peninsula, the northern coast of South China Sea (SCS; the biggest enclosed marginal sea of Western Pacific), to reconstruct East Asian monsoon climate history. This method of using corals from different periods to reconstruct paleoclimate was successfully used in revealing early Holocene abrupt Sr/Ca–SST changes in southwest Pacific (Beck et al., 1997; Gagan et al., 2000). South China Sea is a major moisture source region, providing summer monsoon rainfall throughout Mainland China, which accounts for more than 80% total precipitation in the region (An et al., 2000; Zheng et al., 1983). The study area, Leizhou Peninsula, is located on the northern fringe of the tropical area, and is part of the tropical monsoon climate regime of Southeast Asia. According to instrumental records, the period of 1990–1999 AD was the warmest decade during last 50 years at this area. Worldwide, the warm climate of 1990s has resulted a series of climate problems, such as stronger El Niño activities (Giannini et al., 2001), coral reef bleaching (Stone et al., 1999), and retreat of mountain glaciers (Su and Shi, 2002). In this study, we attempt to reconstruct SST and East Asian monsoon history in the region since mid-Holocene and to understand whether the recent warming is simply part of a natural climatic cycle or caused by anthropogenic impacts.

2. The study site and its environmental conditions

The coral reef (20°13–17′N, 109°54–58′E) is located at Leizhou Peninsula (Fig. 1) and it is the only developed and well-preserved coral fringing reef on the Mainland China. The reef flat, dominated as *Goniopora* and *Porites*, is about 10 km long and 500–1000 m wide (2 km wide at most), from which multiple Holocene sea level high-stands (Nie et al., 1997; Yu et al., 2002b; Zhao and Yu, 2002) and mid-Holocene (7.0–7.5 ky BP) high-frequency winter-cooling events (Yu et al., 2004) were reconstructed.

This coral reef area is part of the tropical monsoon climate regime. From June to August, this area,

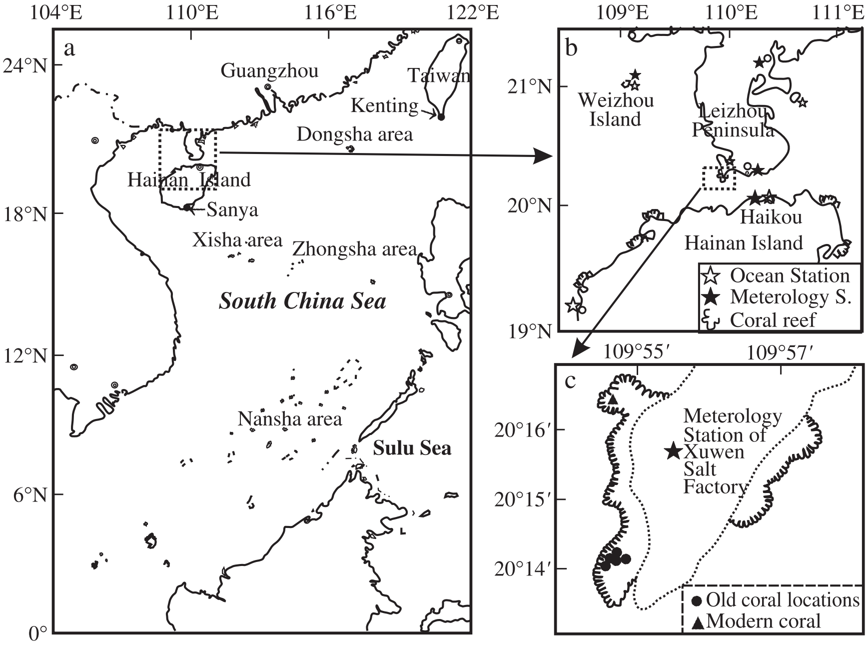


Fig. 1. The location maps of the coral reef at Leizhou Peninsula. (a) Leizhou Peninsula is located at the northern coast of South China Sea; (b) the coral reef at Leizhou Peninsula and the nearby ocean and meteorology stations; (c) sample localities.

together with the whole South China Sea, provides moisture supply for summer monsoon rainfall throughout east part of China. From October to March the next year, the NW winter monsoon prevails, which brings cold and dry continental air from Siberian and Mongolian highs, resulting in reduced precipitation in China. Instrumental data from the nearby meteorological observatory at Xuwen Salt Factory, 1.5 km away from the sampling site, show that since 1975 the mean annual air temperature, rainfall, evaporation and sunshine duration are 24.2 °C, 1102.3 mm, 1721.5 mm, and 2098.8 h, respectively. Table 1 outlines the monthly climate parameters in the vicinity of the coral reef. Information on the local geology, climate, coral reef geomorphology, coral reef distribution, coral ecology and Holocene sea level changes were reported in our previous publications (Yu, 1998; Yu, 2000; Yu et al., 2002a,b, 2004; Zhao and Yu, 2002).

Table 1
Monthly climate parameters for the coral reef area

	Month												Annual average/total
	1	2	3	4	5	6	7	8	9	10	11	12	
SST (°C)	19.1	19.0	20.8	23.7	27.2	29.2	30.0	29.9	28.9	26.8	23.6	20.6	24.9
Air temperature (°C)	17.5	18.2	21.2	24.8	27.5	29.1	29.4	28.9	27.6	25.4	21.7	18.6	24.2
Sunshine duration (h/month)	125.5	103.9	135.9	168.8	215.2	216.1	244.5	209.5	174.0	189.7	165.8	150.0	2098.8
Cloud cover	6.1	6.7	5.9	5.8	6.3	6.9	6.1	6.6	5.6	5.0	5.0	5.2	5.9
Precipitation (mm/month)	13.0	25.1	23.7	55.4	72.6	149.1	148.5	202.9	220.1	142.4	38.9	20.6	1102.3
Evaporation (mm/month)	93.0	85.4	117.9	144.8	185.0	186.7	205.8	175.2	149.4	150.3	123.1	104.4	1721.5
SSS (‰)	32.5	32.6	32.5	32.5	32.6	32.0	32.0	31.2	31.5	31.9	31.8	32.1	32.1

Sea surface temperature (SST) data from Haikou Ocean Observatory, located in 47 km distance to the sampling site, are based on the period of 1960–2000 AD. Air temperature, sunshine duration, cloud cover, precipitation, and evaporation data from the Meteorological Observatory of Xuwen Salt Factory, located 1.5 km to the sampling site, are based on the period of 1975–2000 AD. Sea surface salinity (SSS) data from the Ocean Observatory of Weizhou Island, in 110 km distance to the sampling site, are based on the period of 1960–1994 AD. See Fig. 1 for locations.

3. Materials and experiment

Five *Porites lutea* samples (DLO-06, DLO-07R, DLO-14, DLO-11 and DLO-05) with TIMS U-series ages of 6789±43, 5906±28, 5011±54, 2541±24 and 1513±22 years BP (relative to 2000 AD) (Zhao and Yu, 2002) (corresponding to 4789±43 BC, 3906±28 BC, 3011±54 BC, 541±24 BC, 487±22 AD, see Table 2), collected from the low-tidal emerged reef flat of Leizhou Peninsula (Fig. 1), were selected for this study. For comparison, a modern *P. lutea* (DLL-05) collected from the reef front zone of the same reef, growing at water depth of 0.8 m during low tide, was also analyzed.

All the samples were scanned with X-ray diffraction technology in the Laboratory of Mar. Geol., Tongji University (Shanghai, China) and the results reveals no evidence for diagenesis or alteration as non-aragonite components are all below detection level. This inference is supported by the fact that four of the five Holocene samples have $\delta^{234}U(T)$ values of 146±3 to 153±3, analytically indistinguishable from those of modern pristine corals (149±4) (Stirling et al., 1998). Sample DLO-7R has a $\delta^{234}U(T)$ value of 157±3, slightly above the range for modern corals, implying that this sample may have suffered minor secondary disturbance, causing slight U mobilisation and redistribution.

We first cut an ~1-cm-thick slab with a high-speed diamond saw in the direction of the major growth axis from each coral sample. Then X-ray images of the dried coral slabs were taken using a hospital X-ray equipment for examination of annual growth bands.

The coral slabs were soaked in 10% H_2O_2 for 24 h, followed by washing with deionized water for 5 to 10 min in order to decompose organic matter completely. It was ultrasonically cleaned in deionized water for 30 min to eliminate contaminants on the surface, and then dried.

Using the X-ray images as location guide, sub-annual samples were sliced or scraped with a very thin stainless steel blade along the major growth axis under a stereomicroscope. The average sampling resolution was about 0.5 mm, a total of 529 sub-annual samples were collected from the five mid–late Holocene corals at a resolution of 8 to 16 samples per year depending on their growth rates. A total of 130 samples were collected from the modern coral at about 0.6–0.8 mm interval, corresponding to an average temporal resolution of 12–13 samples per year. Each sub-annual sample was about 10–15 mg.

Coral $\delta^{18}O$ were measured following the standard procedures on a Finnigan MAT 252 mass spectrometer with an automatic carbonate device (Kiel III) in the Mar. Geol. Laboratory of Tongji University, Shanghai, China. Analytical precision and reproducibility were regularly monitored with a Chinese national carbonate standard (GBW04405) and an international standard NBS19. Repeated measurements of the standard vary around a standard deviation (2σ) of 0.07‰ (Tian et al., 2002), corresponding to an uncertainty in calculated SST of ~0.4 °C (see calibration equation below).

Coral Sr/Ca was measured with an inductively coupled plasma atomic emission spectrometer (ICP-AES) at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, following the method first developed by Schrag (1999). For each sub-annual sample, about 2–3 mg fraction was completely dissolved in 1% HNO_3 and the solution was diluted to 10,000 times (to 20–30 g). About 10 ml aliquot was used for Sr/Ca measurements. The instrument is

Table 2
Mean coral Sr/Ca values and their corresponding SSTs

Sample name	Age (years BC/AD)	$\delta^{234}U(T)$	Number of years in the profile	Mean of Sr/Ca annual lows (mmol/mol)	Mean of annual SST maxima (°C)	Mean of Sr/Ca annual highs (mmol/mol)	Mean of annual SST minima (°C)	Mean annual SST (°C)[a]
DLO-06	4789±43 BC	152±2	9	8.521	31.0	8.971	20.4	25.7
DLO-07R	3906±28 BC	157±3	11	8.593	29.3	8.908	21.9	25.6
DLO-14	3011±54 BC	153±3	10	8.553	30.3	8.987	20.0	25.1
DLO-11	541±24 BC	146±3	11	8.593	29.3	9.008	19.5	24.4
DLO-05	487±22 AD	149±3	13	8.620	28.7	9.137	16.5	22.6
DLL-05	1989–2000AD	–	11	8.590	29.4	8.976	20.3	24.8

[a] Mean (or median) annual SST is the average between the mean of SST maxima and that of SST minima.

equipped with CCD detectors for simultaneous collection of all spectral lines within the analyzed wave range. This will significantly reduce the analytical uncertainty resulting from the fluctuation of signal intensity caused by plasma instability, improving overall analytical precision to better than 1% in the raw data. Instrumental drift was monitored and corrected by measuring an internally established laboratory standard at intervals. The drift correction further improves the analytical precision, resulting in an overall precision of ~0.2% for Sr/Ca, corresponding to an uncertainty in calculated SST of ~0.4 °C (see calibration equation below). Detailed analytical procedure was reported by Wei et al. (2004).

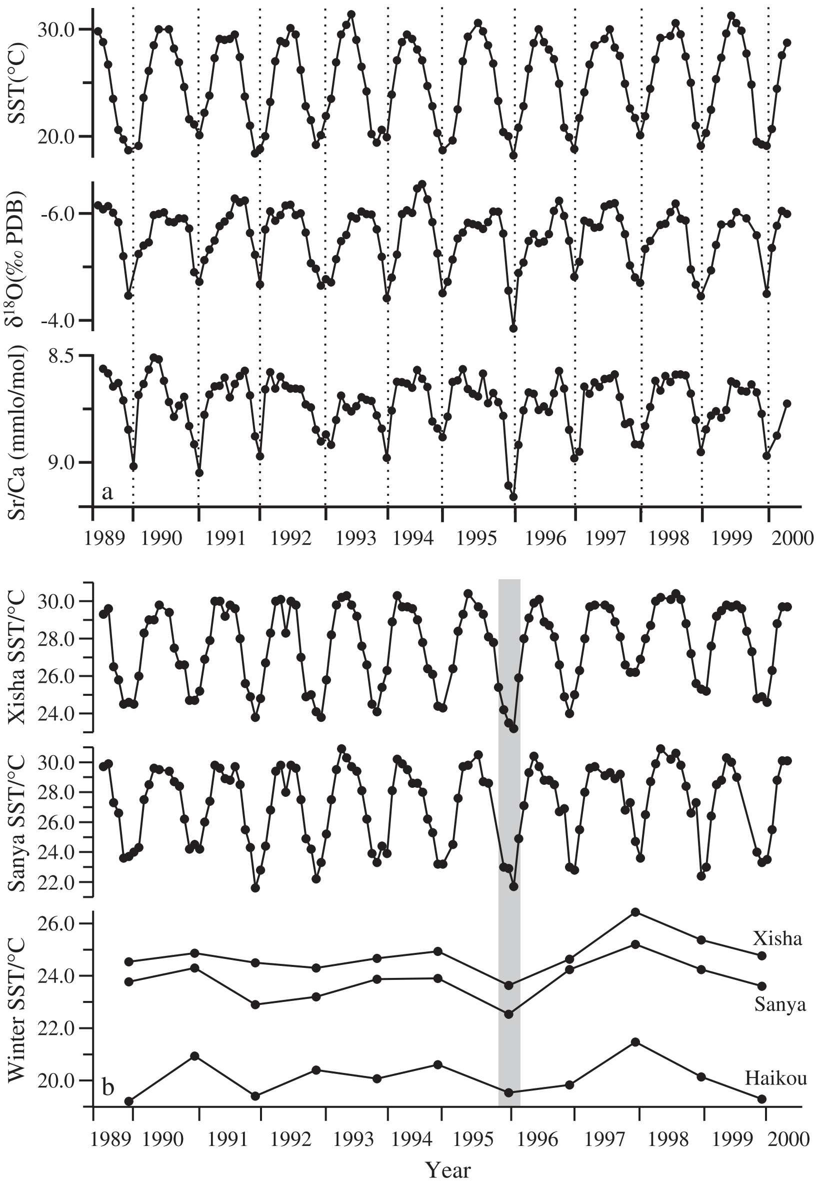


Fig. 2. (a) Modern *P. lutea* (1989–2000 AD) Sr/Ca and $\delta^{18}O$ profiles for comparison with instrumental SST from Haikou Station. (b) Instrumental SST profiles from Haikou, Xisha and Sanya stations. Note that both Xisha and Sanya (located to the south of Haikou) display a cold winter anomaly in 1995–1996, which is not obvious in the Haikou records. See text for discussion.

4. Results

The experimental results show that both the Sr/Ca and $\delta^{18}O$ of the modern coral have clear annual cycles similar to the instrumental SST record from the nearest Haikou Station (Fig. 2a). The profiles have broad peaks in summer and narrow troughs in winter, suggesting the coral grew faster in summer than in winter. Similar to the modern coral, Sr/Ca and $\delta^{18}O$ results of the Holocene corals all display very clear annual cycles with broad peaks in summer and the ranges of Sr/Ca and $\delta^{18}O$ values are comparable to those of the modern coral (Fig. 3).

To obtain the most representative calibration equations, we first smoothed the SST data to the sampling resolution of the modern coral record (monthly resolution for summer and seasonal-resolution for winter), and then matched the maximum $\delta^{18}O$ value with the minimum SST value and the minimum $\delta^{18}O$ value with the maximum SST value in any given year. Then we match the midpoints of the SST curves with those of the $\delta^{18}O$ limbs. The coral $\delta^{18}O$ values between the maximum, minimum and midpoint values were then matched with the smoothed SST record. The same approach was also used for the Sr/Ca profiles. Regressions between the Sr/Ca and $\delta^{18}O$ results and the matched instrumental SST data (using Isoplot/EX program of Ludwig, 1999) yield the following calibrations (errors at 2σ level):

$$\delta^{18}\mathrm{O} = -0.174(\pm 0.010) \times \mathrm{SST}\ (^{\circ}\mathrm{C}) - 1.02(\pm 0.27)\ (\mathrm{MSWD} = 5.8) \quad (1)$$

$$\mathrm{Sr/Ca}_{(\mathrm{mmol/mol})} = -0.0424(\pm 0.0031) \times \mathrm{SST}\ (^{\circ}\mathrm{C}) + 9.836(\pm 0.082)\ (\mathrm{MSWD} = 8.6) \quad (2)$$

Eq. (1) indicates a slope for $\Delta\delta^{18}O/\Delta SST$ of −0.174‰/°C, suggesting that an SST increase of 1 °C corresponds to a decrease in skeletal $\delta^{18}O$ of 0.174‰, very similar to the neighbouring Hainan Island (South China Sea) of −0.187‰/°C (He et al., 2002) and the −0.189‰/°C in Taiwan (Shen, 1996). Eq. (2) indicates a slope for $\Delta(Sr/Ca)/\Delta SST$ of −0.0424 mmol/mol/°C, suggesting that an SST increase of 1 °C corresponds to a decrease in skeletal Sr/Ca of 0.0424 mmol/mol, which is within error of the slope of 0.046 mmol/mol/°C reported for a *P. lutea* coral from Sanya (Fig. 1a), Hainan Island (Wei et al., 2000), and is only marginally lower than the values (~0.051) reported for *P. lutea* corals at Xisha (Fig. 1a) of South China Sea (Sun et al., 2004), Kenting reef

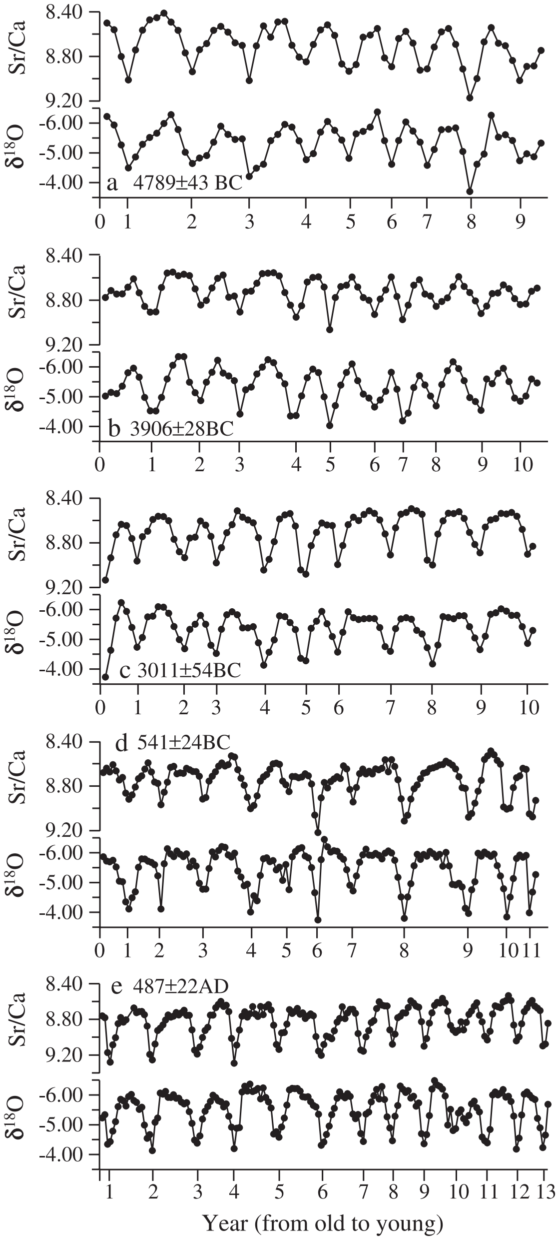


Fig. 3. Sr/Ca (mmol/mol) and $\delta^{18}O$ (‰ PDB) profiles of the mid–late Holocene corals showing clear annual cycles similar to those of the modern coral.

(Fig. 1a), southern Taiwan (Shen et al., 1996), and Galapagos Islands, Eastern Pacific (Schrag, 1999).

It is worthwhile to mention that both δ^{18}O and Sr/Ca records in the modern coral show an anomalously colder winter in 1995–1996, which is not obvious in the Haikou instrumental records (Fig. 2a). However, this winter cooling is clearly seen in instrumental records from many other stations of the northern South China Sea, such as Xisha and Sanya to the south of Haikou (Fig. 2b). Other meteorological records also indicate the winter of 1995–1996 was unusually cold, which killed banana plants in the vicinity of the coral reef. This suggests that the δ^{18}O and Sr/Ca–SST anomalies in 1995–1996 are real and the lack of a similar cold surge in the Haikou instrumental record was likely due to the fact that the station is within Haikou City, the provincial city of Hainan, where SST cooling may have been buffered by industrial activities.

5. Discussion

5.1. Interpretation of Sr/Ca and δ^{18}O-SST relationships

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 (Alibert and McCulloch, 1997; Beck et al., 1992, 1997; Gagan et al., 1998; Marshall and McCulloch, 2002; McCulloch et al., 1994; Mitsuguchi et al., 2003; Shen et al., 1996; Wei et al., 2000), except for some upwelling zones such as the Eastern Pacific where local artifacts may be produced by upwelling of deep ocean water with an unusual Sr/Ca ratio (de Villiers et al., 1994). Because Sr and Ca both have long residence times (~4 My) in ocean water, and Sr and Ca inventories in river runoffs are negligible relative to their concentrations in the seawater, seawater Sr/Ca should be relatively constant on 100,000-year time scale (Gagan et al., 1998; McCulloch et al., 1994). For this reason, coral Sr/Ca should be an ideal proxy for SST at least for the past 100 ka.

Unlike Sr/Ca, coral δ^{18}O is a function of both SST and sea surface salinity (SSS), with SSS varying in response to effective precipitation or evaporation (evaporation–precipitation (E–P)). Thus a combination of coral Sr/Ca and δ^{18}O parameters is capable of solving both past SST and seawater δ^{18}O variations uniquely (Gagan et al., 1998; McCulloch et al., 1994). For instance, seasonal SSS in the vicinity of the reef site varies by up to 1.4‰ (Table 2), which may result in ~0.38‰ variation in seawater δ^{18}O based on the linear relationship between seawater δ^{18}O and SSS (Fairbanks et al., 1997). This accounts for ~20% of the average seasonal variation observed in the modern coral.

Several recent case studies point to Sr/Ca and δ^{18}O variability between colonies of the same site that may demise the environmental/paleoclimatic application of the two proxies. For instance, Allison (1996) reported high spatial resolution ion-probe analyses of Sr/Ca in several coral colonies that grew during the same period. The results show that the mean of overlapping Sr/Ca–SST records varied by up to 4.1 °C between nearby colonies. However, this difference cannot be used to support inter-colony variability due to much larger external uncertainty of the ion-probe data for Sr/Ca (up to ~4% or ~7 °C). A more thorough study of inter-colony δ^{18}O variability was reported for *Porites* corals at Clipperton Atoll (Linsley et al., 1999), which reveals a 0.4‰ difference in mean δ^{18}O between overlapping records from six colonies. However, as pointed out by Linsley et al. (1999), their reproducibility study represents the near worst-case scenario due to the complex relationship between a small annual SST range and a large ITCZ salinity variation at Clipperton. The unusually poor correlation between δ^{18}O and SST (r^2=0.19–0.40) is a clear manifestation of such a problem. On the contrary, most other studies in the literature tend to indicate that inter-colony Sr/Ca and δ^{18}O variability was not a major issue for concern for most other reef sites (e.g. Gagan et al., 1998; Mitsuguchi et al., 2003; Watanabe et al., 2002).

5.2. Possible causes of atypical Sr/Ca–SST calibrations

Recently many researchers discussed the differences in Sr/Ca–SST calibrations and the potential causes (de Villiers et al., 1995; Gagan et al., 2000; Marshall and McCulloch, 2002; Shen et al., 1996). The slope and intercept of our calibration are significantly lower than those of most other calibrations (Gagan et al., 2000; Marshall and McCulloch, 2002) but are similar to those reported by Sun et al. (2004), Wei et al. (2000) and Shen et al. (1996) for the same region, and by Schrag (1999) for East Pacific. Marshall and McCulloch (2002) considered that the regional variation in coral Sr/Ca–SST relationships is real, depending upon specific environments that control coral physiology.

Apart from the above interpretation, there might be also other possibilities. For instance, the atypical calibration in this study may be due to mismatch of Sr/Ca data to the instrumental SST and thus artificial rotation of the calibration curve, which may occur if the coral has not recorded the whole winter component of the seasonal cycle. In a study of a Japanese coral (32°N), Fallon et al. (1999) found major changes in growth rate within each annual cycle and suggested that growth ceased for several months over the winter of each year. Although it is likely in a high-latitude site like Japan, we think this possibility does not apply to the corals in this study based on the following reasons: (1) the reef site in our study (~20°N) is ~12° lower in latitude and is therefore much warmer than the Japanese site of Fallon et al. (1999). With a winter minimum SST in the range of 18–21 °C, it is very unlikely that *Porites* corals will cease growth. In addition, the winter minimum SST in Xisha over the past 40 years is ~24 °C, ideal for corals to growth, yet the calibration slope (0.051 mmol/mol) reported by Sun et al. (2004) is still significantly lower than the typical 0.062 mmol/mol. (2) In our separate high-resolution Sr/Ca study of the same reef (Yu et al., 2004), we found that subtle instrumental SST variations during winter seasons are clearly reflected in the skeletal Sr/Ca trends of a modern *Goniopora* coral we used for calibration, implying that the coral was growing during the full winter season. Similarly, we also demonstrate that Holocene *Goniopora* corals at the same site survived winter cooling to below 15 °C. Since the branchy corals like *Goniopora* are more vulnerable to SST extremes than massive corals like *Porites*, we think that the modern *Porites* coral in this study must also be continuously growing during the whole winter seasons.

Another possibility for such an atypical calibration is that the sampling resolution is too low to reveal the detailed pattern of the winter-time SST due to significantly lower extension rates in winter, causing distortion of the calibration. Watanabe et al. (2002) suggest that, to resolve the full range of annual SST, 40 analyses per year is preferred. The sampling resolution for the modern coral in this study is at 12–13 samples per year, which is probably too low. However, to circumvent this problem, we have assigned instrumental mean winter-season SST for the Sr/Ca maximum and instrumental monthly maximum SST for the Sr/Ca minimum. This treatment should minimise the distortion of the calibration caused by seasonal difference in sampling resolution. If we match the Sr/Ca maxima to monthly SST minima, then the slope will be even smaller, at 0.0375 mmol/mol.

To further assess the above possibilities, we here use only the annual maximum and minimum Sr/Ca values to construct the Sr/Ca–SST relationship (Gagan et al., 1998; Sun et al., 2004). It was found that if we match the Sr/Ca maxima to monthly mean SST minima and do the regression, the slope is 0.0378 mmol/mol. If we match the annual Sr/Ca maxima to the mean winter SSTs (3-month means), and the Sr/Ca minima still to monthly mean SST maxima, then the regressed slope increases to 0.0396 mmol/mol. To increase the regressed slope to the typical 0.062 mmol/mol, we have to increase the winter mean SST by up to 4 °C from 18.9–20.9 to 22.9–24.9 °C, approaching the April mean at Haikou Station, which is highly unrealistic. In a word, this test suggests that even if the slope of our Sr/Ca–SST relationship has been distorted by sampling-resolution problem, the real slope should still be lower than the typical value of 0.062 mmol/mol. Because of this, we agree with Marshall and McCulloch (2002) that the regional variation in coral Sr/Ca–SST relationships is real. Further study based on higher resolution sampling is underway to clarify this problem.

Before using the established Sr/Ca–SST relationship to reconstruct the Holocene SST, another issue also needs to be considered. The three mid-Holocene corals have relatively slower growth rates. Since the faster a colony grows the more likely it is that a sample will capture the winter extreme, one may argue that the winter minimum SSTs reconstructed for the mid-Holocene may not be as low as the true values. Although this is a potential problem, we think the impact on reconstructed winter SSTs is not significant. This is because the sampling resolution is still at approximately nine samples per year and at this resolution there should still be one to two samples capturing the winter season. According to instrumental records, the modern mean winter SSTs are not significantly different from the monthly mean SST minima. On the other hand, since coral grows faster in summer, the sampling resolution for all six corals analyzed in this study should be at least monthly for the summer season and therefore the reconstructed summer SST maxima should still be reliable. In fact, with the exception of the 3906±28 BC sample whose Sr/Ca may be affected by minor secondary disturbance, the other two Holocene samples reveal an annual SST range of 10.3–10.6 °C, similar to that of the present day, suggesting that the impact of sampling artifacts on winter SST minima is insignificant (Table 2).

5.3. Reconstruction of SST and salinity change in South China Sea

South China Sea is a moisture source region for East Asian monsoon rainfall in the mid-latitude region. Even in the vicinity of the sampling site, which is located at the northmost of South China Sea and receives monsoon rainfall from moisture drawn from further south, the present annual evaporation there still surpasses annual precipitation by ~619 mm (E–P) (Table 1). When annual SST is high, effective evaporation will increase, creating more moisture for the summer monsoon. This process will distill isotopically lighter oxygen isotope into the water vapor that is transported by atmosphere (e.g. monsoonal winds) polarward, leaving behind a seawater characterized by higher δ^{18}O and higher SSS. Thus, by extracting the SST component of the δ^{18}O variation based on the difference between coral Sr/Ca and δ^{18}O curves (Gagan et al., 1998), the residual δ^{18}O should represent a measure of change in effective evaporation or moisture level of past summer monsoon relative to the present day. The residual δ^{18}O can be calculated using the following equation: $\Delta\delta^{18}\text{O}=\text{d}\delta^{18}\text{O}/\text{d}T\times(T_{\delta 18_{\text{O}}}-T_{\text{Sr/Ca}})$, which represents the deviation from mean modern seawater δ^{18}O. In this equation, $\text{d}\delta^{18}\text{O}/\text{d}T$ is the slope of the empirical δ^{18}O–SST relationship, and $T_{\delta 18\text{O}}$ and $T_{\text{Sr/Ca}}$ represent calculated SSTs based on the empirical δ^{18}O– and Sr/Ca–SST relationships, respectively.

To obtain numeric constraints on long-term SST change and its relationship to East Asian summer monsoon in the Holocene, we first calculated Sr/Ca–SST for individual data, and worked out annual SST maxima and minima for each coral. We then calculate the 9- to 13-year means of the maxima and minima for each coral that covers a period of 9–13 years, and obtain the mean annual SST by averaging the coupled maxima and minima. The use of means will minimise the impact of analytical errors and shorter term variabilities on longer term SST estimates. In addition, we calculate the residual δ^{18}O ($\Delta\delta^{18}$O) for individual analysis using the above equation and then work out the mean for each coral sample (see Fig. 4). $\Delta\delta^{18}$O profiles appear to be noisier than those of Gagan et al. (1998, 2000), but do show annual cycles similar to Sr/Ca and δ^{18}O cycles. The noise might be due to cumulative errors derived from analytical uncertainties of Sr/Ca (which might be larger than those of TIMS results) and δ^{18}O, seawater Sr/Ca variations, as well as shorter term climatic variabilities.

Fig. 5 shows the relationships between calculated $\Delta\delta^{18}$O and precipitation, evaporation and effective precipitation (precipitation–evaporation) for the modern coral. It can be seen that $\Delta\delta^{18}$O is well correlated with both the precipitation and the effective precipitation, with precipitation or effective-precipitation peaks generally matching with negative $\Delta\delta^{18}$O troughs. Such trends suggest that during annual monsoon-rainfall season in the vicinity of the reef site (July–October), monthly mean δ^{18}O of the local seawater from which the coral grows (which also receives monsoon-rainfall as it is located to the north margin of South China Sea) excurses to more negative values (negative $\Delta\delta^{18}$O), and SSS reaches annual lows (Table 1). During other seasons when the effective precipitation is low, seawater δ^{18}O is less negative (positive $\Delta\delta^{18}$O) and SSS is higher. In a word, the relationship suggests that an increase in the amount of isotopically lighter monsoon moisture being transported to mid-latitude region is capable of raising the mean seawater δ^{18}O in South China Sea, and vice versa.

Based on a combination of Sr/Ca and δ^{18}O data for the Holocene corals, past climate information for the following time windows can be obtained (see Fig. 4 and Table 2).

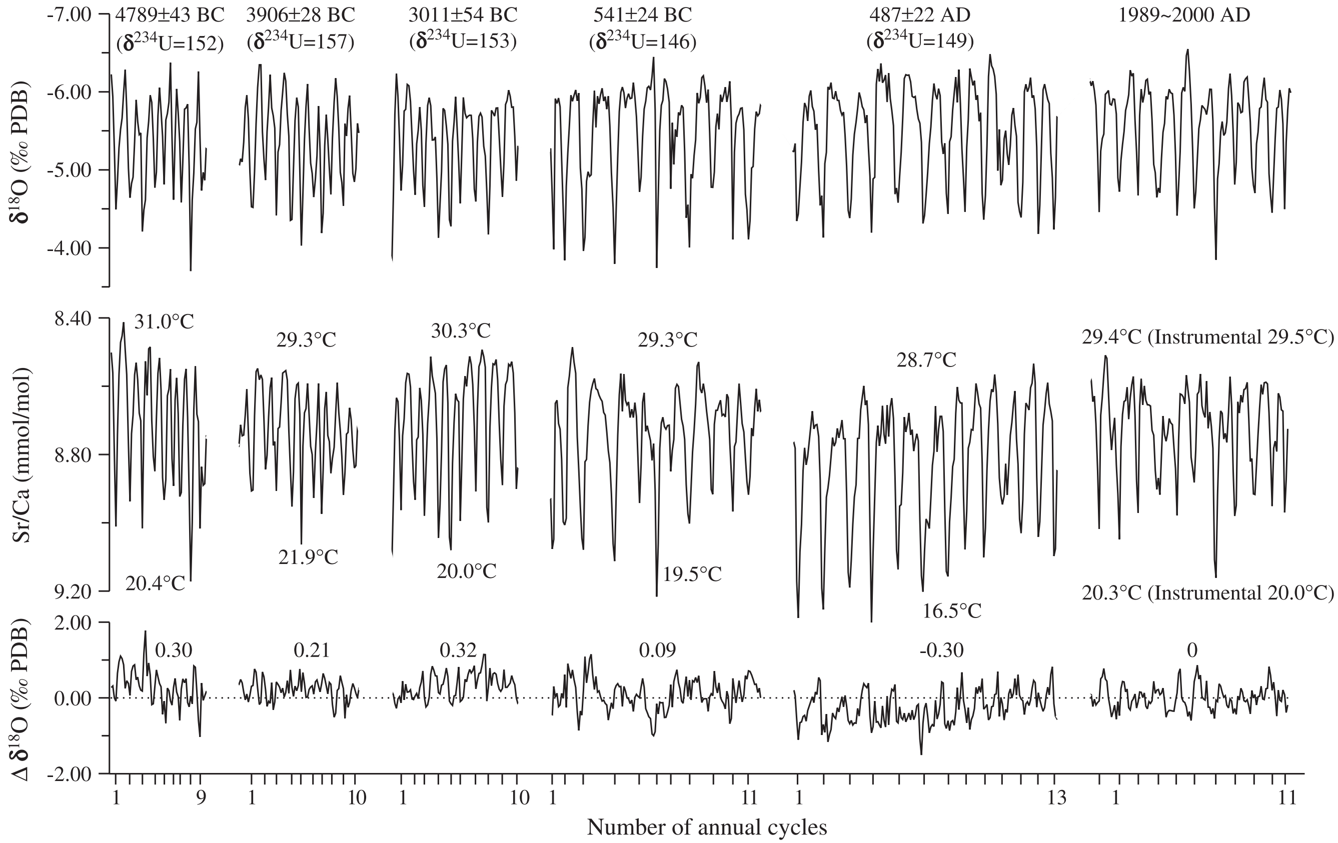


Fig. 4. Mid–late Holocene and modern coral Sr/Ca and δ^{18}O series and corresponding $\Delta\delta^{18}$O. The ages of the corals, their initial δ^{234}U, mean summer and winter Sr/Ca–SST and mean $\Delta\delta^{18}$O values are also shown for comparison. See text for discussion.

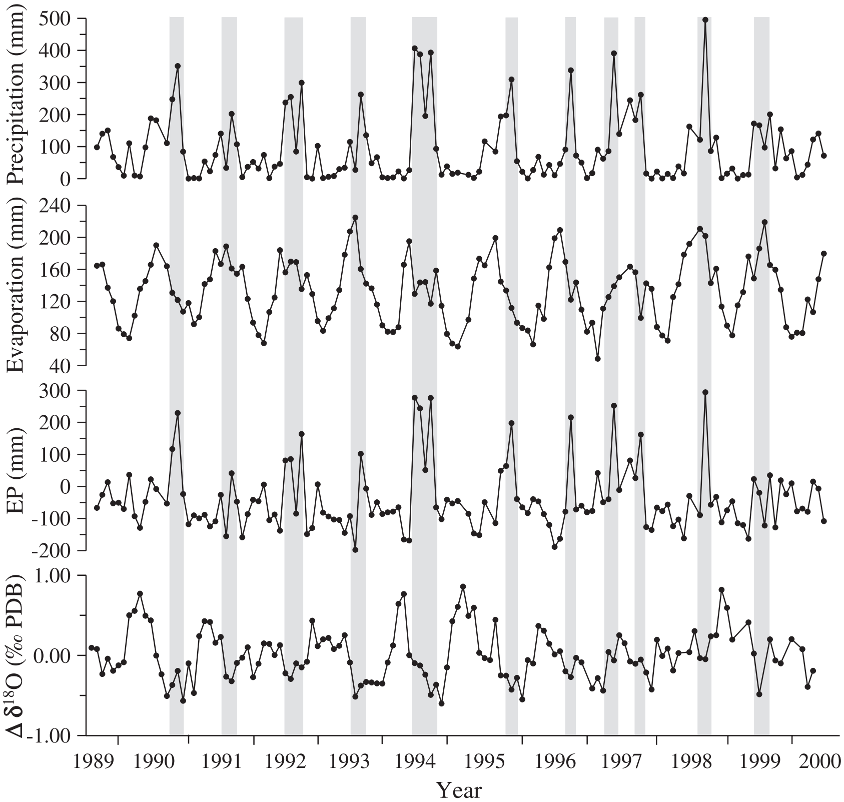


Fig. 5. $\Delta\delta^{18}O$ values for the modern coral and their comparison with instrumental records which shows that lower $\Delta\delta^{18}O$ is correlated with higher precipitation and higher effective precipitation (EP=precipitation–evaporation).

5.3.1. ~6789 years BP (~4789 BC)

This time window is represented by sample DLO-06 (6789±43 years BP), which covers a profile of 9 years, with coral Sr/Ca varying between 8.41 and 9.17 mmol/mol and $\delta^{18}O$ varying between −3.70‰ and −6.38‰. The calculated 9-year mean summer maximum Sr/Ca–SST is 31.0 °C (Table 2), about 1.6 °C higher than mean summer maximum Sr/Ca–SST in the 1990s (29.4 °C); winter Sr/Ca–SST is 20.4°C, similar to that in the 1990s (20.3 °C). The average annual Sr/Ca–SST is 25.7°C, ~0.9 °C higher than mean annual Sr/Ca–SST in the 1990s (~24.8 °C). Mean $\Delta\delta^{18}O$ is +0.3‰, suggesting that oxygen isotopes of the seawater of that time was +0.3‰ heavier than that of the 1990s. In other words, this suggests that the amount of moisture transported out of South China Sea was higher than in the 1990s and summer monsoon was stronger. Our previous studies indicate that the modern coral reef geomorphologic framework took its shape during 6300–7200 years BP (Yu et al., 2002b), with over 70% of surface massive corals at this reef flat forming during this period (Zhao and Yu, 2002). This suggests climatic conditions during the mid-Holocene, especially 6300–7200 years BP, such as stability of sea level, SST and SSS, were ideal for the corals to grow. In addition, pollen and lake level records from Mainland China show that the mid-Holocene climate was relatively warmer and wetter (An et al., 2000; Shi et al., 1993). These are all consistent with our findings that SST of South China Sea at ~6.8 ky was generally warmer, and the sea-surface evaporation was higher.

5.3.2. ~5906 years BP (~3906 BC)

This time window is represented by sample DLO-07R, which covers a period of 11 years, with an Sr/Ca range of 8.55–9.06 mmol/mol and a $\delta^{18}O$ range of

−4.03‰ to −6.35‰. Like the ~6.8-ky-old sample DLO-06, the 11-year mean annual Sr/Ca–SST is ~25.6 °C, ~0.8 °C higher than in the 1990s (Table 2). The mean $\Delta\delta^{18}O$ of +0.2‰ is also similar to that of the ~6.8-ky-old sample, which suggests that the amount of moisture transported out of South China Sea was higher, and summer monsoon stronger, than the present day. These are all consistent with independent pollen and lake-level record of the Mainland China (Shi et al., 1993). However, a major discrepancy exists in the annual summer SST highs and winter SST lows, which appear to be the reverse if compared with the situation ~6.8 ky ago. The mean summer SST (~29.3 °C) was ~1.7 °C lower than ~6.8 ky ago, whereas the mean winter SST (~21.9 °C), ~1.5 °C warmer. A cool summer with a warm winter is quite unexpected. If this is real, the seasonal SST contrast was only ~7.4 °C, ~3.2 °C smaller than in ~6.8 ky ago, with both summer and winter monsoons being significantly weaker. There is no independent evidence to suggest this is the case. We consider that a smaller seasonal SST contrast is merely an artifact of mobility and partial redistribution of coral Sr on millimeter scale, as reflected by slightly elevated $\delta^{234}U$ in DLO-07R (157±3, see Fig. 4) relative to the normal range of 149±4. Since the Sr mobility and partial redistribution process is localized, the mean annual SST has not been affected. A detailed study of vandose-zone diagenesis (McGregor and Gagan, 2003) shows that formation of 1% diagenetic calcite will raise calculated coral Sr/Ca–SST by 1.1 to 1.5 °C, and calculated $\delta^{18}O$-SST by −0.2 to 0.2 °C. We do not think that this applies to our case as no diagenetic calcite was found in our sample. It is more likely that Sr/Ca redistribution process only occurred on small scales in a relatively closely system without significant geochemical exchange with the environment. Further work will be carried out on a fresher sample of the same age to verify this possibility.

5.3.3. ~5011 years BP (~3011 BC)

This time window is represented by sample DLO-14 which covers a period of 10 years with coral Sr/Ca and $\delta^{18}O$ falling into the ranges of 8.49–9.13 mmol/mol and −3.73‰ to −6.23‰, respectively. Its 10-year mean summer Sr/Ca–SST is 30.3 °C (Table 2), about 0.9 °C higher than in the 1990s; winter Sr-Ca SST ~20.0 °C, similar to the 1990s. The average annual Sr/Ca–SST is ~25.2 °C, ~0.5 °C higher than in the 1990s. The mean $\Delta\delta^{18}O$ is +0.32‰, which suggests that the amount of moisture transported out of South China Sea was higher, and summer monsoon stronger, than in the 1990s. Again, this inference is consistent with pollen and lake-level records of Mainland China (An et al., 2000; Shi et al., 1993).

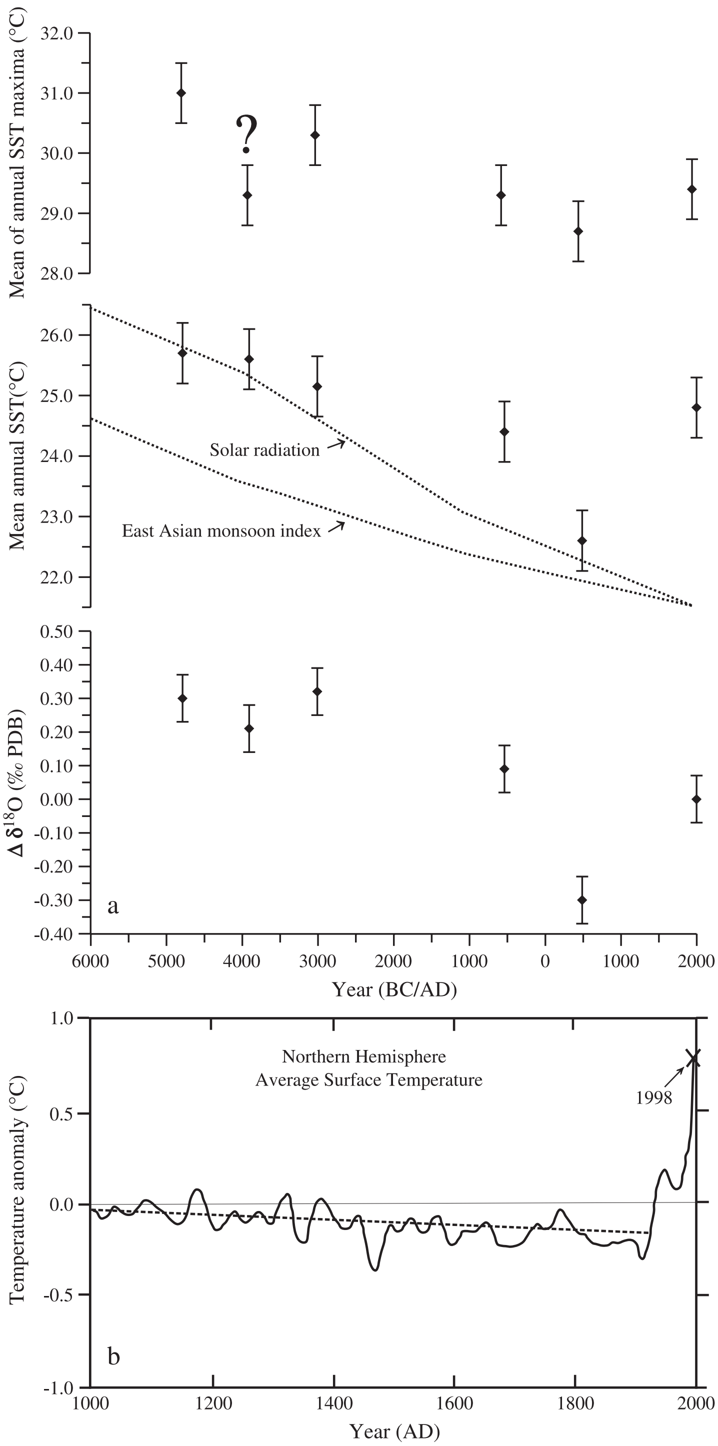
5.3.4. ~2541 years BP (~541 BC)

This time window is represented by sample DLO-11, which covers a period of 11 years, with coral Sr/Ca ranging from 8.49 to 9.22 mmol/mol and $\delta^{18}O$ from −3.74‰ to −6.45‰. The 11-year mean summer Sr/Ca–SST (Table 2) is 29.3 °C, very similar to that of the 1990s; and winter Sr/Ca–SST 19.5 °C, about 0.7 °C lower than in the 1990s. The average annual Sr/Ca–SST is about 24.4 °C, ~0.4 °C lower than in the 1990s, which is analytically insignificant. The mean $\Delta\delta^{18}O$ is 0.09‰, which is also indistinguishable from that of the 1990s, implying a somehow similar climate condition to that of the 1990s (the warmest period of the last century). Historic records show that it was relatively warm and wet in China about 2539 years ago (~541 BC, the War Kingdom) (Chu, 1973), which is consistent with our finding.

5.3.5. ~1513 years BP (487 AD)

This time window is represented by sample DLO-05 that covers a period of 13 years. The 13-year mean summer Sr/Ca–SST (Table 2) is 28.7 °C, about 0.8 °C lower than in 1990s; mean winter Sr/Ca–SST is 16.5 °C, ~3.8 °C lower than in 1990s. The average annual

Fig. 6. (a) Long-term trend of mean of annual SST maxima, mean annual SST (the average of annual maximum and minimum) and $\Delta\delta^{18}O$ for comparison with solar radiation intensity and East Asian monsoon index (after An et al., 2000). Note that both SST and $\Delta\delta^{18}O$ (a measure of summer monsoon moisture level) display a decreasing trend till 1.5 ky ago, consistent with the weakening of Northern Hemisphere solar radiation and East Asian summer monsoon. The mean of annual SST maxima for the 3906±28 BC sample is questionable due to minor Sr/Ca mobility. A nominal SST uncertainty of ±0.5 °C is used in the plots, which is based on the analytical uncertainty of Sr/Ca ratios and the regression errors in the calibration equation. See text for discussion. (b) Northern Hemisphere average surface temperature showing the reversal of the natural trend since the beginning of the 20th century (after Mann et al., 1999).


Mean of annual SST maxima (°C)
32.0
31.0
30.0
29.0
28.0
?
Mean annual SST(°C)
26.0
25.0
24.0
23.0
22.0
Solar radiation
East Asian monsoon index
Δ δ18O (‰ PDB)
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
a
6000
5000
4000
3000
2000
1000
0
1000
2000
Year (BC/AD)
Temperature anomaly (°C)
1.0
0.5
0.0
-0.5
-1.0
Northern Hemisphere
Average Surface Temperature
1998
b
1000
1200
1400
1600
1800
2000
Year (AD)

Sr/Ca–SST is ~22.6 °C, ~2.2 °C lower than in the 1990s. The mean $\Delta\delta^{18}O$ is −0.30‰, which suggests that the amount of moisture transported out of South China Sea was lower, and summer monsoon weaker, than in the 1990s. The above findings are clearly consistent with Chinese historical records (Chu, 1973; Ge et al., 2002), which indicate that the period of 450–530 AD was significantly colder and drier in east China.

5.4. Implications for Holocene monsoon climate and modern climate trend

In summary, our results reveal a general decreasing trend in sea surface temperature (SST) and seawater $\delta^{18}O$ in South China Sea from ~6800 to 1500 years ago. Compared with the mean Sr/Ca–SST in the 1990s (24.8 °C), 10-year mean Sr/Ca–SSTs were 0.9–0.5 °C higher between 6.8 and 5.0 ky BP, dropped to the present level by ~2.5 ky BP, and reached a low of 22.6 °C (2.2 °C lower) by ~1.5 ky BP (Fig. 6, Table 2). If only summer maximum SSTs, which are more reliable, are considered, the trend remains the same, with the mid-Holocene SSTs being 1–2 °C warmer, and the SST at ~1.5 ky BP being 0.7 °C lower, than in the 1990s. Such a decline in SST till ~1.5 ky BP (Fig. 6a) is accompanied by a similar decrease in effective evaporation, resulting in a general decrease in the seawater $\delta^{18}O$ values, reflected by the offsets of mean $\delta^{18}O$ relative to that in the 1990s. This trend will not change if different calibration equations (Marshall and McCulloch, 2002) are used, although the absolute values of the calculated SSTs and $\Delta\delta^{18}O$ are different.

Holocene climate change in terms of East Asian summer monsoon precipitation (effective moisture) has been reconstructed using lake levels, pollen records and loess/paleosol profiles throughout mainland China (An et al., 2000; Shi et al., 1993; Chen et al., 2001) as well as marine sediment cores from South China Sea (Wang et al., 1999). Despite shorter term millennial climatic oscillations (Jian et al., 2000; Wang et al., 1999), all published records show that summer monsoon intensity in China peaked during the Early–mid Holocene (~9 ky BP), and then gradually weakened until today, in response to a continuous decay in solar radiations in the Northern Hemisphere. The decrease in summer monsoon strength is reflected in the southeastward shift of the East Asian summer monsoon maximum (An et al., 2000). Our SST and seawater $\delta^{18}O$ records from South China Sea for the period of 6.8–1.5 ky BP are clearly consistent with continuous weakening of East Asian summer monsoon (Fig. 6a).

However, this trend was reversed in recent time, characterized by a significantly higher SST and SSS (higher seawater $\delta^{18}O$) in the 1990s than would be expected based on the solar radiation trend. Such a departure from the natural trend, which is consistent with recent atmospheric CO_2 change (Petit et al., 1999) and the trend of the average surface temperature in the Northern Hemisphere (Mann et al., 1999) (Fig. 6b). The trends in CO_2 and surface temperature clearly indicate that anthropogenically generated greenhouse gases in the atmosphere have played a dominant role in raising up the global temperature. Although the latest two time windows are 1500 years apart, we believe that, with analyses of more corals for this time period, a clearer picture of environmental response to human activities in South China Sea can be obtained.

6. Conclusions

The combination of monthly to seasonal-resolution Sr/Ca and $\delta^{18}O$ data of five Holocene and one modern *P. lutea* corals suggests that mid-Holocene sea surface temperatures (SST) in South China Sea were warmer and East Asian summer monsoon precipitation higher than in the 1990s, consistent with many other independent records. Both SST and the intensity of summer monsoon declined in the late Holocene, reaching a minimum by ~1.5 ky ago, probably in response to a continuous decay in solar radiations in the Northern Hemisphere. This natural trend in recent time was reversed as a result of phenomenal increase in anthropogenic greenhouse gases in the atmosphere (Petit et al., 1999), which resulted in general global warming and a significant rise in the SST and seawater $\delta^{18}O$ in South China Sea.

Acknowledgements

This paper was presented at the International Young Scientists' Global Change Conference, organized by START (hhttp://www.start.org) and hosted by the Third World Academy of Sciences/ICTP in Trieste, Italy in November 16–19, 2003. This work was funded by the National Science Foundation of China (No. 40231009), the Chinese Ministry of Science and Technology Special Scheme (No. 2002CCA02700 and G2000078502) and the knowledge Innovation Project of the Chinese Academy of Sciences (KZCX3-SW-220). Zhao, Yu and Wei acknowledge the support of an NSFC Distinguished Young Scholar Award (No. 40028302). Yu would like to thank Prof. Tungsheng Liu for long-term guidance, and thank A/Prof. Chen Tegu, Dr. Zhimin Jian and Dr. T. Felis for constructive comments. This paper benefit tremendously from constructive reviews of two anonymous reviewers.

References

Alibert, C., McCulloch, M.T., 1997. Strontium/calcium ratios in modern Porites corals from the Great Barrier Reef as a proxy for sea surface temperature: calibration of the thermometer and monitoring of ENSO. Paleoceanography 12 (3), 345–363.

Allison, N., 1996. Comparative determinations of trace and minor elements in coral aragonite by ion microprobe analysis, with preliminary results from Phuket, southern Thailand. Geochim. Cosmochim. Acta 60 (18), 3457–3470.

An, Z.S., Porter, S.C., Kutzbach, J.E., Wu, X.H., Wang, S.M., Liu, X.D., Li, X.Q., Zhou, W.J., 2000. Asynchronous Holocene optimum of the East Asian monsoon. Quat. Sci. Rev. 19 (8), 743–762.

Beck, J.W., Edwards, R.L., Ito, E., Taylor, F.W., Recy, J., Rougerie, F., Joannot, P., Henin, C., 1992. Sea-surface temperature from coral skeletal strontium calcium ratios. Science 257 (5070), 644–647.

Beck, J.W., Recy, J., Taylor, F., Edwards, R.L., Cabioch, G., 1997. Abrupt changes in early Holocene tropical sea surface temperature derived from coral records. Nature 385 (6618), 705–707.

Chen, F.H., Zhu, Y., Li, J.J., Shi, Q., Jin, L.Y., Wunemann, B., 2001. Abrupt Holocene changes of the Asian monsoon at millennial- and centennial-scales: evidence from lake sediment document in Minqin Basin, NW China. Chin. Sci. Bull. 46 (23), 1942–1947.

Chu, K., 1973. A preliminary study on the climatic fluctuations during the last 5000 years in China. Sci. China, Ser. B-Ser. 16 (2), 226–256.

Correge, T., Delcroix, T., Recy, J., Beck, W., Cabioch, G., Le Cornec, F., 2000. Evidence for stronger El Nino-Southern Oscillation (ENSO) events in a mid-Holocene massive coral. Paleoceanography 15 (4), 465–470.

de Villiers, S., Shen, G.T., Nelson, B.K., 1994. The Sr/Ca–temperature relationship in coralline aragonite—influence of variability in (Sr/Ca) seawater and skeletal growth-parameters. Geochim. Cosmochim. Acta 58 (1), 197–208.

de Villiers, S., Nelson, B.K., Chivas, A.R., 1995. Biological-controls on coral Sr/Ca and delta-O-18 reconstructions of sea-surface temperatures. Science 269 (5228), 1247–1249.

Fairbanks, R.G., Evans, M.N., Rubenstone, J.L., Mortlock, R.A., Broad, K., Moore, M.D., Charles, C.D., 1997. Evaluating climate indices and their geochemical proxies measured in corals. Coral Reefs 16, S93–S100.

Fallon, S.J., McCulloch, M.T., van Woesik, R., Sinclair, D.J., 1999. Corals at their latitudinal limits: laser ablation trace element systematics in Porites from Shirigai Bay, Japan. Earth Planet. Sci. Lett. 172 (3–4), 221–238.

Gagan, M.K., Ayliffe, L.K., Hopley, D., Cali, J.A., Mortimer, G.E., Chappell, J., McCulloch, M.T., Head, M.J., 1998. Temperature and surface-ocean water balance of the mid-Holocene tropical Western Pacific. Science 279 (5353), 1014–1018.

Gagan, M.K., Ayliffe, L.K., Beck, J.W., Cole, J.E., Druffel, E.R.M., Dunbar, R.B., Schrag, D.P., 2000. New views of tropical paleoclimates from corals. Quat. Sci. Rev. 19 (1–5), 45–64.

Ge, Q.S., Zheng, J.Y., Fang, X.Q., 2002. Winter temperature variation in eastern China over the past 2000 years. Quat. Res. 22, 166–173 (in Chinese).

Giannini, A., Chiang, J.C.H., Cane, M.A., Kushnir, Y., Seager, R., 2001. The ENSO teleconnection to the tropical Atlantic Ocean: contributions of the remote and local SSTs to rainfall variability in the tropical Americas. J. Climate 14 (24), 4530–4544.

He, X.X., Liu, D.Y., Peng, Z.C., Liu, W.Q., 2002. Monthly sea surface temperature records reconstructed by delta O-18 of reef-building coral in the east of Hainan Island, South China Sea. Sci. China, Ser. B Chem. 45, 130–136.

Hendy, E.J., Gagan, M.K., Alibert, C.A., McCulloch, M.T., Lough, J.M., Isdale, P.J., 2002. Abrupt decrease in tropical Pacific Sea surface salinity at end of little ice age. Science 295 (5559), 1511–1514.

Jian, Z.M., Wang, P.X., Saito, Y., Wang, J.L., Pflaumann, U., Oba, T., Cheng, X.R., 2000. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. Earth Planet. Sci. Lett. 184 (1), 305–319.

Linsley, B.K., Messier, R.G., Dunbar, R.B., 1999. Assessing between-colony oxygen isotope variability in the coral Porites lobata at Clipperton Atoll. Coral Reefs 18 (1), 13–27.

Ludwig, K.R., 1999. Users manual for Isoplot/EX version 2, a geochronological toolkit for Microsoft excel. Berkeley Geochronol. Cent. Spec. Publ. 1a, 43.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophys. Res. Lett. 26 (6), 759–762.

Marshall, J.F., McCulloch, M.T., 2002. An assessment of the Sr/Ca ratio in shallow water hermatypic corals as a proxy for sea surface temperature. Geochim. Cosmochim. Acta 66 (18), 3263–3280.

McCulloch, M.T., Gagan, M.K., Mortimer, G.E., Chivas, A.R., Isdale, P.J., 1994. A high-resolution Sr/Ca and delta-O-18 coral record from the Great-Barrier-Reef, Australia, and the

1982–1983 El-Niño. Geochim. Cosmochim. Acta 58 (12), 2747–2754.

McGregor, H.V., Gagan, M.K., 2003. Diagenesis and geochemistry of Porites corals from Papua New Guinea: implications for paleoclimate reconstruction. Geochim. Cosmochim. Acta 67 (12), 2147–2156.

Mitsuguchi, T., Matsumoto, E., Uchida, T., 2003. Mg/Ca and Sr/Ca ratios of Porites coral skeleton: evaluation of the effect of skeletal growth rate. Coral Reefs 22 (4), 381–388.

Nie, B.F., Chen, T.G., Liang, M.T., Zhong, J.L., Yu, K.F., 1997. Coral reefs from Leizhou Peninsula and Holocene sea level highstands. Chin. Sci. Bull. 42 (5), 511–514 (in Chinese).

Petit, J.R., et al., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399 (6735), 429–436.

Schrag, D.P., 1999. Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. Paleoceanography 14 (2), 97–102.

Shen, C.C., 1996. High precision analysis of Sr/Ca ratio and its environmental application, PhD thesis, Chinese Academy of Sciences (Taiwan), Teipei, 183 pp.

Shen, C.C., Lee, T., Chen, C.Y., Wang, C.H., Dai, C.F., Li, L.A., 1996. The calibration of D[Sr/Ca] versus sea surface temperature relationship for Porites corals. Geochim. Cosmochim. Acta 60 (20), 3849–3858.

Shi, Y.F., Kong, Z.Z., Wang, S.M., Tang, L.Y., Wang, F.B., Yao, T.D., Zhao, X.T., Zhang, P.Y., Shi, S.H., 1993. Mid-Holocene climates and environments in China. Glob. Planet. Change 7 (1–3), 219–233.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. Earth Planet. Sci. Lett. 160 (3–4), 745–762 (Aug.).

Stone, L., Huppert, A., Rajagopalan, B., Bhasin, H., Loya, Y., 1999. Mass coral reef bleaching: a recent outcome of increased El Niño activity? Ecol. Lett. 2 (5), 325–330.

Su, Z., Shi, Y.F., 2002. Response of monsoonal temperate glaciers to global warming since the little ice age. Quat. Int. 97-8, 123–131.

Sun, Y.L., Sun, M., Wei, G.J., Lee, T., Nie, B.F., Yu, Z.W., 2004. Strontium contents of a Porites coral from Xisha Island, South China Sea: a proxy for sea-surface temperature of the 20th century. Paleoceanography 19 (2) (PA2004, doi:10.1029/2003PA000959).

Tian, J., Wang, P.X., Cheng, X.R., Li, Q.Y., 2002. Astronomically tuned Plio-Pleistocene benthic delta O-18 record from South China Sea and Atlantic-Pacific comparison. Earth Planet. Sci. Lett. 203 (3–4), 1015–1029.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Heilig, S., Ivanova, E., Kienast, M., Pelejero, C., Pflaumann, U., 1999. East Asian monsoon climate during the late Pleistocene: high-resolution sediment records from the South China Sea. Mar. Geol. 156 (1–4), 245–284.

Watanabe, T., Winter, A., Oba, T., Anzai, R., Ishioroshi, H., 2002. Evaluation of the fidelity of isotope records as an environmental proxy in the coral Montastraea. Coral Reefs 21 (2), 169–178.

Wei, G.J., Sun, M., Li, X.H., Nie, B.F., 2000. Mg/Ca, Sr/Ca and U/Ca ratios of a porites coral from Sanya Bay, Hainan Island, South China Sea and their relationships to sea surface temperature. Palaeogeogr. Palaeoclimatol. Palaeoecol. 162 (1–2), 59–74.

Wei, G.J., Yu, K.F., Li, X.H., Zhao, J.X., Sun, Y.L., Sun, M., 2004. Coralline Sr/Ca thermometer for the northern South China Sea: calibration and primary application on high-resolution SST reconstructing. Quat. Sci. 24 (3), 325–331 (in Chinese).

Yu, K.F., 1998. Near-shore climate fluctuation of the Leizhou Peninsula during 1950–1997. Mar. Sci. Bull. 17 (5), 24–29 (in Chinese).

Yu, K.F., 2000. The sea surface temperature changing trend of the last 40 years in the Lei-Qiong sea area. Trop. Geogr. 20 (2), 111–115 (in Chinese).

Yu, K.F., Liu, D.S., Shen, C.D., Zhao, J.X., Chen, T.G., Zhong, J.L., Zhao, H.T., Song, C.J., 2002a. High-frequency climatic oscillations recorded in a Holocene coral reef at Leizhou Peninsula, South China sea. Sci. China, Ser. D-Earth Sci. 45 (12), 1057–1067.

Yu, K.F., Zhong, J.L., Zhao, J.X., Shen, C.D., Chen, T.G., Liu, D.S., 2002b. Biological-geomorphological zones in a coral reef area at southwest Leizhou Peninsula unveil multiple sea level highstands in the Holocene. Mar. Geol. Quat. Geol. 22 (2), 27–33 (in Chinese).

Yu, K.F., Zhao, J.X., Liu, T.S., Wei, G.J., Wang, P.X., Collerson, K.D., 2004. High-frequency winter cooling and coral mortality during the Holocene climatic optimum. Earth Planet. Sci. Lett. 224 (1–2), 143–155.

Zhao, J.X., Yu, K.F., 2002. Timing of Holocene sea-level highstands by mass spectrometric U-series ages of a coral reef from Leizhou Peninsula, South China Sea. Chin. Sci. Bull. 47 (4), 348–352.

Zheng, S., Hou, F., Ni, B., 1983. C–O isotope study of precipitations in China. Chin. Sci. Bull. 13, 801–806.