Strontium contents of a *Porites* coral from Xisha Island, South China Sea: A proxy for sea-surface temperature of the 20th century

Yali Sun,[1] Min Sun,[1] Gangjian Wei,[1,2] Typhoon Lee,[3] Baofu Nie,[4] and Zhiwei Yu[5]

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[1] A *Porites* coral collected from Xisha Island, South China Sea, represents a skeleton secreted in the period from 1906 to 1994. The Sr contents of the coral vary linearly with the instrument-measured sea-surface temperature (SST), giving a Sr thermometer: $SST = -1.9658 \times Sr + 193.26$. The reconstructed SST data show that the late 20th century was warmer (about 1°C) than the early 20th century and that two cooling (1915/1916 and 1947/1948) and three warming (1935/1936, 1960/1961, and 1976/1977) shifts occurred in the century. The temperature shifts are more pronounced for winters, implying a close effect of the west Pacific warm pool and Asian monsoon and suggesting that the former is a primary force controlling the climatic system of the region. Results of this study and previously published data indicate a close link of temperature shifts between the boreal summer and the austral winter or the boreal winter and the austral summer. The annual SST anomalies in the South China Sea and the South Pacific reveal the existence of harmonic but opposite SST variations between the two regions. On the decadal scale the comparative annual SST anomalies for the South China Sea and for the equatorial west Pacific show a similarity in temperature variations, implying that the South China Sea climate is coherent with climatic regime of the tropical west Pacific. *INDEX TERMS:* 1050 Geochemistry: Marine geochemistry (4835, 4850); 4808 Oceanography: Biological and Chemical: Chemical tracers; 1620 Global Change: Climate dynamics (3309); *KEYWORDS:* coral, strontium, sea-surface temperature

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1. Introduction

[2] Sea-surface temperature (SST) records for tropical oceans provide an essential database for global climatic studies [*Trenberth and Hurrell*, 1994; *Picaut et al.*, 1996; *Latif et al.*, 1996]. Unfortunately, instrument-measured SST data are limited to a few decades and only available for limited locations [*Trenberth*, 1990; *Latif and Barnett*, 1994; *Fairbanks et al.*, 1997]. Therefore reconstruction of long-term paleo-SST records becomes very imperative. Skeletons of massive corals, such as *Porites*, are very useful for such reconstructions, because their chemical and isotopic compositions vary with the SST of the ambient water, and their annual growth bands provide a precise chronology. The relatively high growth rate (about 10 mm/year) for coral skeletons allows very high, e.g., monthly, temporal resolution for subsampling [*Lough et al.*, 1996; *Cole*, 1996]. Consequently, long-lived massive corals have been used to study variations of SST and other environmental parameters, such as meteoric precipitation and evaporation [*Pätzold et al.*, 1992; *Cole et al.*, 1993; *Quinn et al.*, 1996; *Linsley et al.*, 2000a).

[3] Although long-term coral $\delta^{18}O$ records have been obtained for the past several centuries [*Pätzold*, 1986; *Dunbar et al.*, 1994; *Linsley et al.*, 1994; *Quinn et al.*, 1998; *Cobb et al.*, 2001], their interpretation presents a challenge. For example, coral $\delta^{18}O$ data not only vary with SST, but are also affected by hydrographic conditions of the ambient seawater [*Quinn et al.*, 1993; *Linsley et al.*, 1994; *Felis et al.*, 2000]. In contrast, the ratios of some trace elements to Ca, such as Sr/Ca, Mg/Ca and U/Ca in coral skeletons, seem to faithfully record ambient seawater temperature [*Smith et al.*, 1979; *Swart and Hubbard*, 1982; *Min et al.*, 1995; *McCulloch et al.*, 1994; *Mitsuguchi et al.*, 1996; *Wei et al.*, 2000]. Among these ratios, the Sr/Ca ratio has mostly been used in previous studies because coral skeletons possess very high Sr contents (~7500 μg/g; *Sun et al.* [1999]). Accordingly, coral Sr/Ca thermometry has been established for SST studies based on the observed linear relationship between skeletal Sr/Ca ratios and SST records [*Beck et al.*, 1992; *Shen et al.*, 1996; *Alibert and McCulloch*, 1997]. Unfortunately, due to the limited seasonal variation of Sr/Ca

[1]Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong, China.
[2]Also at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China.
[3]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan.
[4]South China Sea Institute of Oceanography, Chinese Academy of Sciences, Guangzhou, China.
[5]College of Mineral Resource and Environment Sciences, China University of Mining and Technology, Beijing, China.

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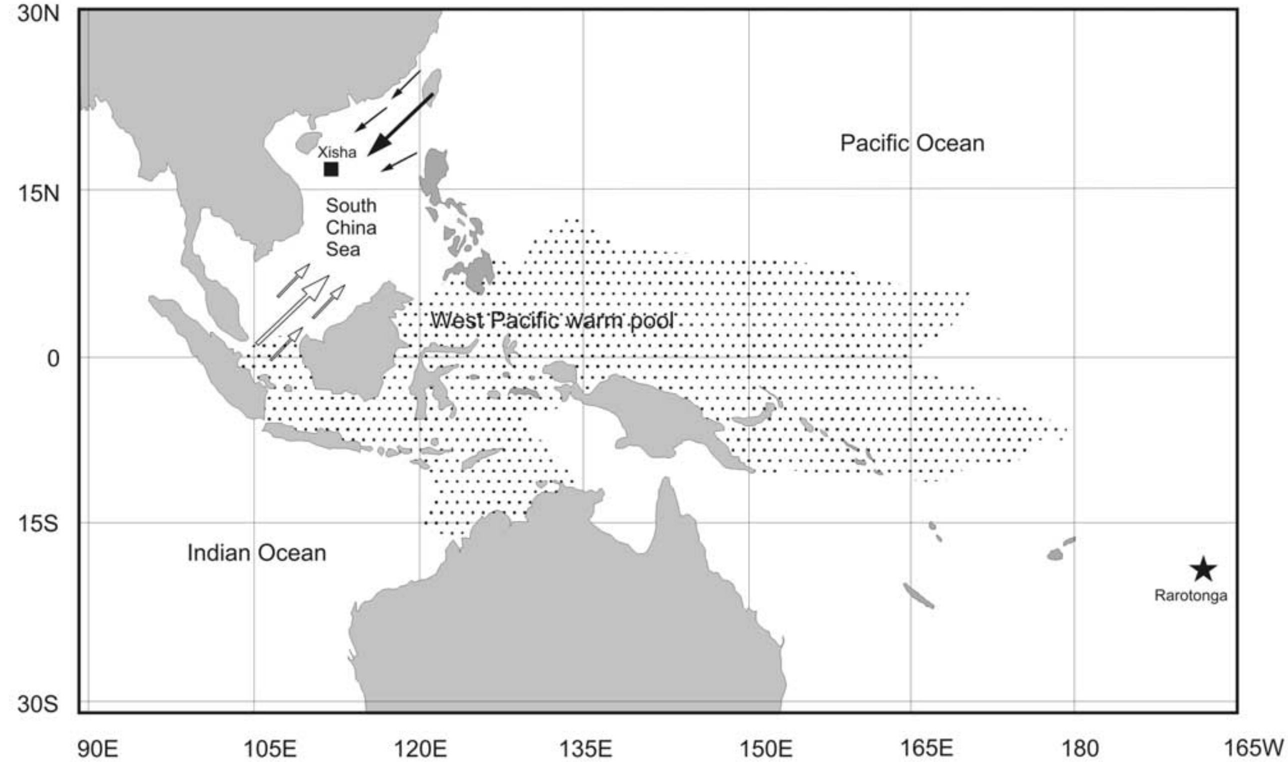

Figure 1. Geographical location of the South China Sea. The solid square shows the collection site of the Xisha coral, and the solid star is for the location of Rarotonga. The longer solid arrow represents the surface wind direction and the shorter solid arrows represent the surface current directions during winter months; and the longer open arrow represents the surface wind direction and the short open arrows represent the surface current directions during the summer months.

ratios in coral skeletons (~3%), the measurement of high quality Sr/Ca ratios requires very high analytical precision such as provided by ID-TIMS (isotope dilution-thermal ionization mass spectrometry) [*Beck et al.*, 1992; *de Villiers et al.*, 1994; *Shen et al.*, 1996; *Alibert and McCulloch*, 1997]. This has greatly hindered the application of coral Sr/Ca thermometry since only a small number of laboratories in the world can conduct such analyses because of the severe mass fractionation of Ca isotopes during the TIMS measurement, although ID-TIMS Sr analysis is routine in numerous laboratories. Because Sr/Ca analysis by this technique is time-consuming, most previous studies have only provided data for a short time period, e.g., several years [*Beck et al.*, 1997; *McCulloch et al.*, 1996, 1999], which helps little in the evaluation of decadal climate variation.

[4] This study uses a *Porites* coral drilled from Xisha Island of the South China Sea, which is about one meter long and covers almost the entire 20th century. Based on the previous finding that the coral sample has a uniform Ca content [*Sun et al.*, 1999], this study aims at establishing a Sr thermometer for the Xisha coral and reconstructing SST records for the last century. Because the South China Sea extends from the west Pacific warm pool to the south coast of the Asian continent, the Pacific decadal oscillation, ENSO and the Asian monsoon all affect the climate of the region. Results of this study will certainly provide necessary data for understanding the climatic system of this important region.

2. Geographic Background

[5] As a large marginal sea of the west Pacific, the South China Sea (SCS) is situated in the meteorologically sensitive zone between the Pacific and Indian Oceans (Figure 1). The SCS region covers both tropical and subtropical areas, and its southern part is close to the west Pacific warm pool, which is intimately related to El Niño [*Trenberth*, 1976; *Picaut et al.*, 1996]. The SCS climate is characterized by two contrasting Asian summer and winter monsoons, one of the most energetic climate systems on Earth [*Liang*, 1991; *Wang*, 1999; *Chen et al.*, 1999]. Southwesterly winds blow over the SCS during the summer months, and northeasterly winds prevail during the winter months. The equatorial tropical water of the west Pacific is brought into the sea by the southwesterly winds through southern straits, whereas extratropical water of the northwest Pacific is driven into the sea by northeasterly winds through the Taiwan Strait. Surface currents of the SCS change seasonally according to the surface wind directions (Figure 1). The amount of water exchange, or water flux, between the SCS and the Pacific depends on monsoon wind speeds and directions [*Wyrtki*, 1961; *Bogdanov and Moroz*, 1995]. Therefore the South

China Sea is an ideal region for studying past climate variability of the Asian monsoon in the west Pacific. For the Pacific Ocean, some instrumental meteorological data are available such as long-term optically smoothed SST data for the equatorial west Pacific [*Kaplan et al.*, 1998]. In addition, several sets of SST records have been reconstructed from coral oxygen isotope data over the last century for the east tropical Pacific [*Dunbar et al.*, 1994], the central tropical Pacific [*Cobb et al.*, 2001] and the southwest subtropical Pacific [*Quinn et al.*, 1998], and Sr/Ca ratios have been determined for a coral from South Pacific [*Linsley et al.*, 2000b]. Obviously, a paleo-SST record of corals from the South China Sea will be a new and valuable asset to the existing Pacific SST data. Reconstruction of long-term paleotemperature records for the South China Sea will help us understand the climatic variability for a wider region of the Pacific.

[6] Xisha Island is located in the northern part of the South China Sea (Figure 1) and is influenced by the typical Asian monsoon and frequent tropical cyclones [*Wang and Fei*, 1987; *Wang*, 1991; *Yan et al.*, 1993]. Under the influence of the Asian monsoon, the area is wet from May to October and dry from November to April of the following year [*Nie et al.*, 1996]. Instrumental records from the Yongxing Oceanographic Station (16°51′N, 112°20′E) at Xisha Island indicate that the lowest and highest monthly SSTs over the period 1961–1994 are 23.8°C in January and 29.5°C in June, respectively. The annual mean SST is 27.3°C, with a seasonal SST range of 6°C. In general, the lowest SST postdates the maximum northeasterly wind by about two months whereas the highest SST is virtually synchronous with the summer monsoon. Annual rainfall is about 1500 mm, mainly in the period from June to October [*Nie et al.*, 1996]. The sea-surface salinity (SSS) fluctuates from 33.3‰ to 34.0‰, with an average of 33.67‰ [*Nie et al.*, 1997]. The large seasonal SST range and the small SSS variation imply that Xisha Island is an ideal site for coral SST studies.

3. Sampling and Methodology

[7] A living *Porites* coral at 20 m water depth was drilled in early June 1994 from Xisha Island (Figure 1) along the dominant axis of growth using a hydraulic drill with 6.0 cm inner diameter core barrel. Upwelling and river discharge do not significantly influence the environmental conditions around the collection site [*Nie et al.*, 1996].

[8] The coral core was rinsed in ambient seawater before transport. The coral sample was sliced into 7 mm thick slabs parallel to its vertical axis and cleaned with deionized water in the laboratory. X-ray photographs were taken in order to examine annual high-density bands for chronological information, and each couplet of low- and high-density bands (HDB) represents yearly growth of the coral. The actual chronology was determined by counting the high-density bands from the top, corresponding to the collection time. The HDB on the bottom of the coral sample represents year 1906.

[9] A microsurgical machine, CHINA 2, was employed for cutting samples to 1 mm depth perpendicular to the maximum extension in 1 mm intervals [*Shen*, 1996; *Shen et al.*, 1996], which corresponds to about a monthly increment of the coral. The saw was then rotated 90° to cut 1 mm grids. Consequently, 1 mm^3 subsamples were collected using a surgical knife and a pair of surgical tweezers. Each of the subsamples (~0.5 mg) for this study was weighed with a microbalance, UMT-5 (sensitive to 0.1 μg), and then dissolved in 0.5 mol/L HCl. A small aliquot of the solution was weighed and mixed with an appropriate amount of ^{84}Sr spike. The mixture was dried on a hot plate and a total of 199 subsamples were analyzed for Sr concentration by VG 354 mass spectrometry in the Institute of Earth Sciences, Academia Sinica (Taipei), whereas the remainder were analyzed in the Institute of Geology and Geophysics, Chinese Academy of Sciences (Beijing), following the method described by *Shen* [1996] and *Shen et al.* [1996]. These subsamples correspond to the time interval from 1906 to 1994. The precision (2σ) of the whole analytical procedure was better than 1.0‰, corresponding to ±0.14°C in temperature. The Xisha coral Sr data are available from the auxiliary material[1].

4. Construction of Coral Sr Thermometer

[10] The Xisha Oceanography Station, about 1.5 km SE of the collection site (Figure 1), has been continuously conducting instrumental measurements of SST since 1961. The coral Sr data for the 18-year interval from 1976 to 1994 are used to see their correlation with the instrument-measured SSTs of the same period, because these data were determined at the Institute of Earth Sciences in Taipei and further checked at the Institute of Geology and Geophysics in Beijing (Figure 2). The coral in this study grew at a rate of about 1.2 cm per year; thus each 1 mm^3 subsample corresponds to approximately one month growth, since coral skeletons may not grow linearly [*Fallon et al.*, 1999; *Cardinal et al.*, 2001]. Previous studies have used either only annual maximum and minimum coral Sr/Ca ratios [*Gagan et al.*, 1998; *Cardinal et al.*, 2001] or all the Sr/Ca ratios for thermometer calibrations [*de Villiers et al.*, 1994; *Shen et al.*, 1996], assuming a linear coral growth in the latter case. *Cardinal et al.* [2001] found that there is no significant difference between the two calibration methods, because the linear line is largely controlled by the extreme data and intermediate data are distributed around the line. In this study, both calibration methods were also applied and the results are essentially the same (Figure 3). Therefore the following equation is used in this study as a Sr thermometer for the Xisha coral, which is derived from the regression of the annual minima and maxima of the coral Sr data with the instrument-measured highest and lowest monthly SSTs:

$$\mathrm{SST} = -1.9658 \times \mathrm{Sr} + 193.26,$$

where Sr is the coral Sr content in μmol/g and SST is the temperature in °C. The correlation coefficient for the calibration is $r^2 = 0.96$.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/pa/2003PA000959.

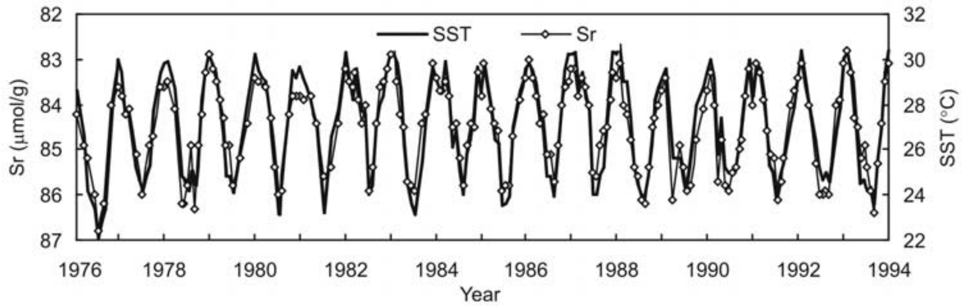

Figure 2. Comparison of Sr contents of Xisha coral with the locally instrument-measured SST record in the period from 1976 to 1994.

[11] The above linearity indicates that coral Sr concentrations closely covary with the ambient water temperature so there is no need to involve Ca in the SST study using the Xisha coral. In fact, the coral Sr thermometry is just a simplification of the conventional Sr/Ca thermometry, because of the uniform Ca content in this coral sample [*Sun et al.*, 1999]. Uniform skeletal Ca content has also been reported for *Porites* corals from Nature Reserve Reef (29.5°N, 34.9°E), northern Red Sea [*Enmar et al.*, 2000], Tarawa Atoll (1°N, 172°E), western Pacific [*Allison et al.*, 2001] and Johnston Atoll (16°N, 169°W), north-central Pacific [*Cohen et al.*, 2001].

5. SST Variations in the South China Sea

[12] The Sr contents of the coral in the growth period of 1906 to 1994 have been converted to SST estimates according to the above Sr thermometer (Figure 3). The reconstructed SST data clearly show seasonal variations (Figure 4), with the annual high from 26.5 to 30.5°C, the annual low from 20.0 to 25.0°C, and a seasonal temperature range of about 6–8°C. These results are broadly concordant with the instrument-measured records post 1961.

5.1. Abnormal Sr-SST Signals for the Period 1973–1975

[13] Despite the broad consistency, the reconstructed annual highest SSTs for 1973 to 1975 are 2–3°C higher than the instrumental records (Figure 4). Similar but smaller disparities in the winters can also be observed during this time interval. This may be the result of a drastic disturbance of the ambient seawater, which invalidated the coral Sr thermometer for the time period. In 1974, there was a navy conflict around this island between China and South Vietnam. Such an event and related military activities in the immediate previous year(s) may have caused an abrupt disturbance of the environment, which might have interfered with feeding processes and zooxanthellar photosynthesis [*Druffel*, 1997] and affected coral Sr intake and growth [*Dodge et al.*, 1974; *Dodge and Vaisnys*, 1977; *Sheppard*, 1980; *Fallon et al.*, 2002]. As a result, the coralline Sr contents in these three years may not provide useful SST information. Fortunately, the problem has no impact on the following discussions, because instrument-measured SST records are available for this period.

5.2. SST Variation in the Last Century

[14] The late 20th century was warmer than the early 20th century, as manifested by both the annual high and the annual low SST records (Figure 4). The mean SSTs are 29.7°C and 24.5°C for the annual high and annual low temperatures, respectively, for the 10-year period from 1984 to 1993. Compared with the SST data for the earliest ten years of the record (1906–1915; 28.9°C and 22.3°C for the annual high and low, respectively), the most recent data show a warming of 0.8°C for the annual high and a warming of 2.2°C for the annual low temperatures.

[15] The global warming of the 20th century has been documented in previous studies by instrumental records combined with data from climatic proxies such as tree rings, ice cores and massive corals [*Hansen and Lebedeff*, 1987; *Charles et al.*, 1997; *Jones et al.*, 1998; *Cole et al.*, 2000]. The available data show an average warming of about 1°C

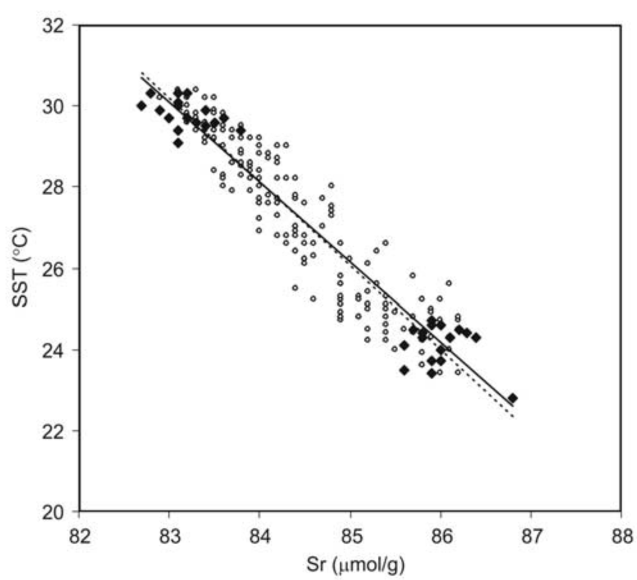

Figure 3. Calibrations of Sr thermometer for the Xisha coral. The solid line is for the annual maxima/minima of data, and the dotted line for all data from 1976 to 1994.

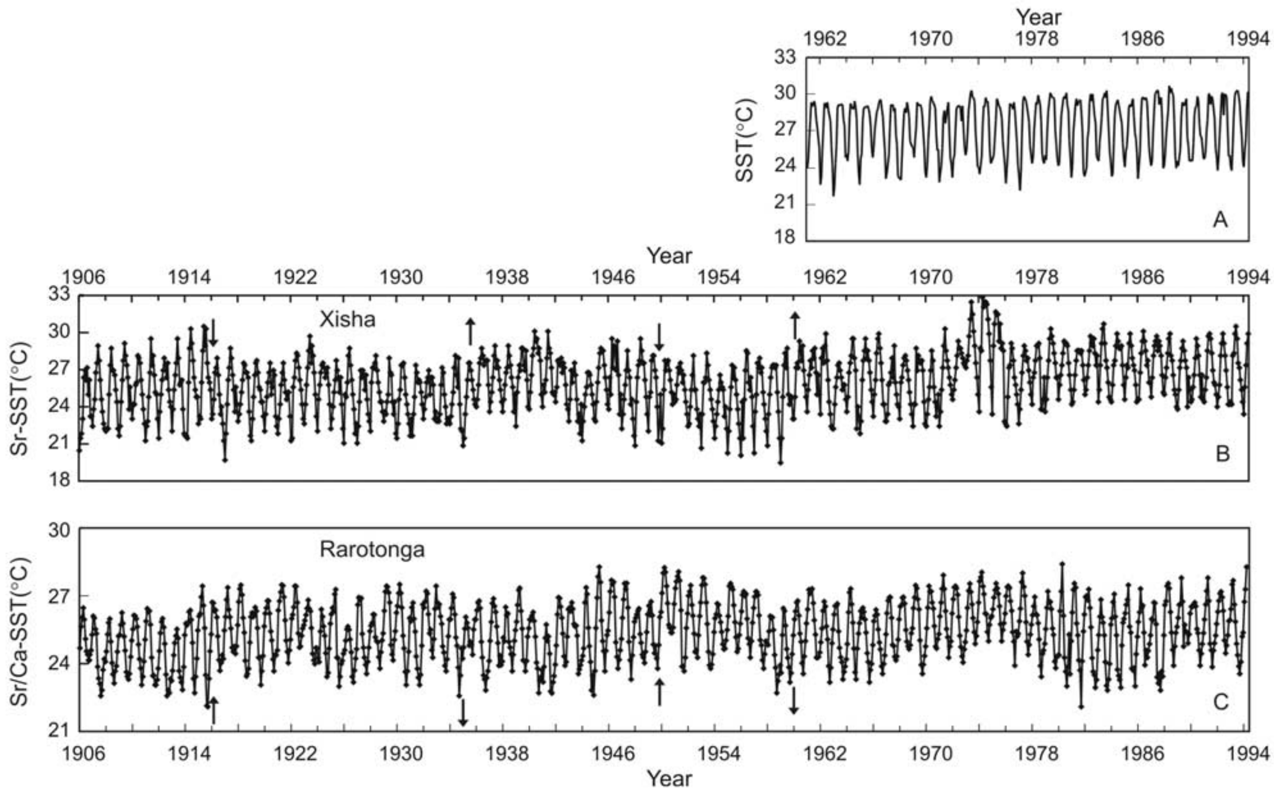

Figure 4. (a) Instrumental SST data (1961 to 1994) from the Yongxing Oceanographic Station (16°51′N, 112°20′E) at Xisha Island. (b) Reconstructed SST data (1906 to 1994) from the Xisha coral Sr record. (c) Reconstructed SST data from the Sr/Ca ratios of a coral from Rarotonga (21.5°S, 159.5°W; *Linsley et al.* [2000b]; from the World Data Center-A for Paleoclimatology, www.ngdc.noaa.gov/paleo/paleo.html).

in the Northern Hemisphere over the past century [*Jones et al.*, 1998]. The amplitude of the summer warming (0.8°C) recorded by the Xisha coral is close to this average. However, the winter warming recorded by the coral is obviously higher. This may imply that winter warming in the South China Sea region was higher than the global average.

[16] Although the SCS experienced a general warming over the last century, the temperature fluctuated on interannual and dominantly decadal scales. Our data reveal the following additional major temperature shifts: 1915/1916 (cooling), 1934/1935 (warming), 1947/1948 (cooling), and 1960/1961 (warming) (Figure 4). The duration of these observed temperature shifts is 19 years from the 1915/1916 cooling to the 1934/1935 warming, 13 years from the 1934/1935 warming to the 1947/1948 cooling, and 13 years from the 1947/1948 cooling to the 1960/1961 warming, respectively. These temperature shifts correlate with the Pacific Decadal Oscillation (PDO) in the North Pacific [*Mantua et al.*, 1997] and are also documented throughout the Pacific by both instrumental data [*Jacobs et al.*, 1994; *Mantua et al.*, 1997; *Minobe*, 1999] and proxy records [*Tudhope et al.*, 1995; *Linsley et al.*, 2000b].

[17] The relatively warmer period in the first half of the century was from 1935 to 1946 despite the occurrence of a brief cooling event from 1942 to 1944. This is consistent with the well-known 1940s warming event [*Hansen and Lebedeff*, 1987; *Jones et al.*, 1998; *Linsley et al.*, 2000a]. In the Xisha coral record, the winter temperature increased by about 1.2°C, but the change of summer temperature was not pronounced, when compared to the beginning of the 20th century. The larger warming amplitude in winters was also previously noticed in the Northern Hemisphere from instrumental records [*Hansen and Lebedeff*, 1987]. The Xisha coralline SST data record a notable cooling in the 1950s, particularly in winter seasons. The average SSTs from 1952 to 1958 were 27.7°C for the annual high and 21.1°C for the annual low. Such a decrease in temperature is not reported for other areas of the Northern Hemisphere. Further investigation is needed to determine whether or not this cooling event is significant in the climate history in the study area.

[18] The Xisha coral also records a continuous warming since the 1960s with a further temperature increase after 1976/1977. This phenomenon has already lasted for more than 40 years, and has attracted the great attention of many scientists [*Trenberth and Hurrell*, 1994; *Miller et al.*, 1994a, 1994b; *Graham*, 1994; *Wang*, 1995].

[19] This study shows that the temperature shifts in the SCS are more obvious in winter (about 1°C amplitude) than in summer (Figure 4). This appears to be a real climatic feature of the region, because the available instrumental SST records show the same phenomenon (Figure 4). The SST in the South China Sea is controlled by both the west Pacific warm pool and the Asian monsoon [*Wyrtki*, 1961;

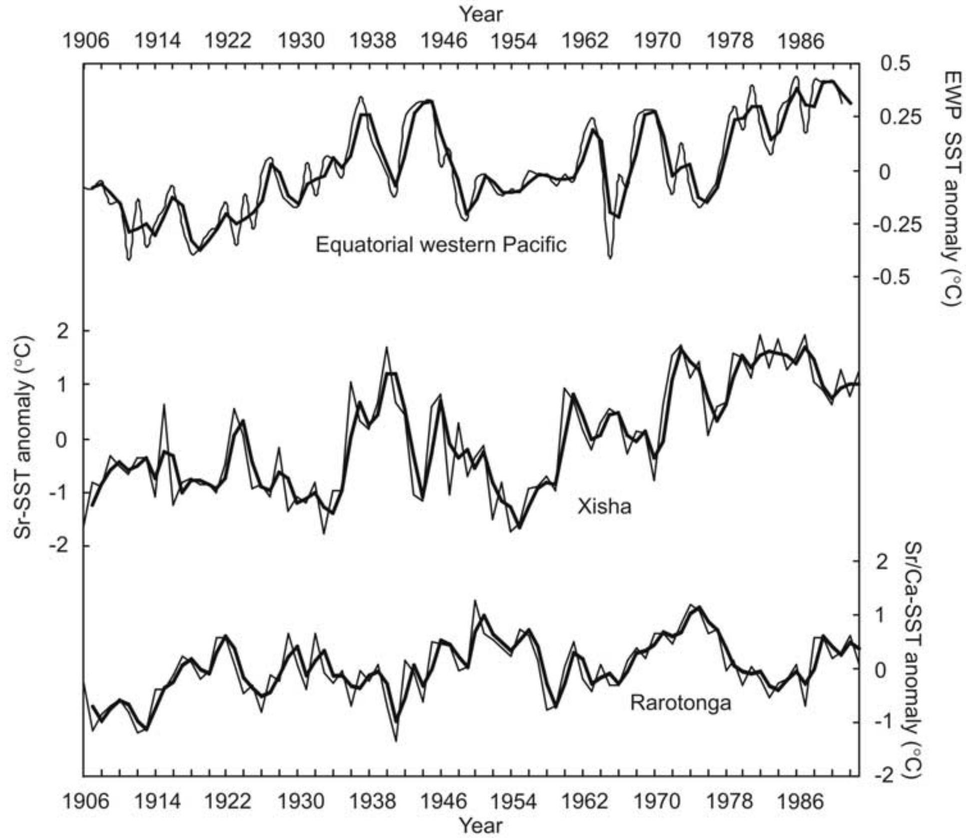

Figure 5. Comparison of annual SST anomalies for South China Sea, Rarotonga [*Linsley et al.*, 2000b], and equatorial west Pacific (5°S–5°N, 120°E–170°E; optically smoothed SST data of *Kaplan et al.* [1998]). The heavy lines represent moving average of two points.

Bogdanov and Moroz, 1995]; it rises in summer immediately upon arrival of the southwesterly monsoon, which brings equatorial tropical water into the sea. It then remains constant at ~29.5°C for 5 months from the end of April to the end of September [*Chu et al.*, 1997], but gradually cools in the winter after the northeasterly monsoon begins. The lowest SST postdates the maximum northeasterly wind by about two months. Recent studies suggest that the Asian winter monsoon becomes weaker when a warming shift occurs [e.g., *Hanawa et al.*, 1989; *Wang et al.*, 2000, 2003; *Peng et al.*, 2003]. This means that in the warming years the winter monsoon brings less extratropical water into the SCS through Taiwan Strait [*Wyrtki*, 1961; *Bogdanov and Moroz*, 1995] and less effectively cools the SCS than in normal years. As a result, the SCS water temperature may experience a larger warming amplitude in the winter than in the summer. This may imply that the west Pacific warm pool is a more dominant factor than the Asian Monsoon in controlling SST variations of the South China Sea.

6. Comparison With Other SST Records of the Pacific Ocean

6.1. Harmonic SST Variations Between the South China Sea and South Pacific

[20] Long time series coral Sr/Ca data have not been provided by the TIMS method. However, *Linsley et al.* [2000b] obtained Sr/Ca ratios for a 271-year period for a coral collected from Rarotonga, South Pacific (Figure 1), using inductively coupled plasma-atomic emission spectrometry (ICP-AES) technology. In order to examine SST variations for the south and north subtropical Pacific in the past century, we compare our reconstructed SST data from the Xisha coral with the SST data from Sr/Ca ratios for the Rarotonga coral.

[21] There appears to be a close link between the boreal summer and the austral winter in term of temperature change (Figure 4). Following are just a few examples: SCS cooler summers correlate with Rarotonga warmer winters during the periods of 1915–1935 and 1947–1958, SCS warmer summers occur with Rarotonga cooler winters during the periods of 1961–1969 and 1977–1989. Similarly, the records show SCS cooler winters and Rarotonga warmer summers for the periods of 1915–1935 and 1947–1958, and SCS warmer winters and Rarotonga cooler summers for the periods of 1961–1969 and 1977–1989.

[22] Using the average SST data as a baseline, annual SST anomalies were calculated for the South China Sea and compared with the annual SST anomalies calculated from the Rarotonga coral Sr/Ca data [*Linsley et al.*, 2000b]. The results clearly demonstrate that the decadal SST variations for the two regions are synchronous but opposite (Figure 5).

[23] This synchronous variation reflects a harmonic response of the Northern and Southern Hemispheres to

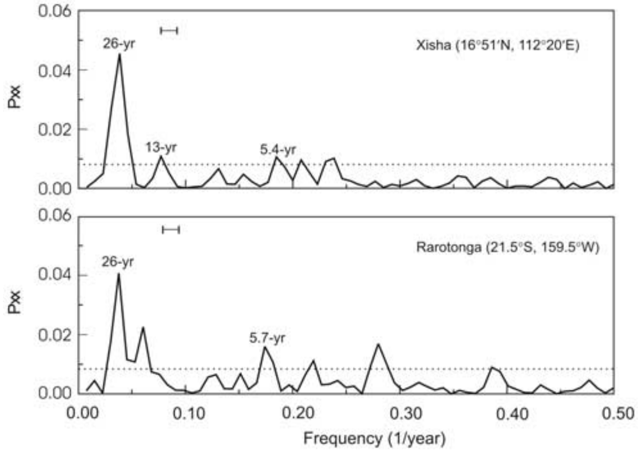

Figure 6. Harmonic spectra of the Xisha coral Sr data and the Rarotonga coral Sr/Ca data. The error bar represents the uncertainty at the 95% confident level.

global climate change on a planetary-scale, which is probably linked to the positive feed-back of the ocean-atmosphere system in the Pacific from subtropical to equatorial regions, arising from the cross-equatorial ocean heat transport [*Bryant*, 1997; *Stocker*, 1998]. The above comparative study demonstrates that long-lived corals are a valuable climatic proxy for the broad investigation of global climate variability, particularly the ocean-atmosphere interactions in the tropical and subtropical Pacific.

6.2. Consistent SST Variation of the SCS With the Equatorial West Pacific

[24] Annual optically smoothed SST (OS-SST) anomalies have been compiled for the equatorial west Pacific (5°S–5°N, 120°E–170°E; *Kaplan et al.* [1998]), which provides an opportunity for us to study the correlation of SST variations for the equatorial region and the SCS. Such a comparison shows the existence of a similarity between the South China Sea and the equatorial west Pacific on a decadal scale (Figure 5), revealing a close SST link between the regions for the last century. The consistent decadal variations are cooling for 1906–35 and 1949–60, warming for 1936–48 and a particularly prolonged warm period of 1961–1993, which includes the striking warming after the 1976/1977 shift in the last century. This consistent SST variation demonstrates that the South China Sea climate is linked to the climatic regime of the tropical west Pacific, and further supports that the SST of the SCS region is primarily controlled by the west Pacific warm pool. This study indicates that the SST variations of the South China Sea can help to investigate the SST variations of the equatorial west Pacific, or the west Pacific warm pool that is responsible for the origin of ENSO. The Asian monsoon is another issue of the climatic system of the region. Previous studies showed that winter Asian monsoon was generally weaker during the mature phase of an El Niño [*Hanawa et al.*, 1989; *Wang et al.*, 2000, 2003], implying an important effect of west Pacific warm pool on Asian winter monsoon. Because both the Asian monsoon and west Pacific warm pool are major forces for climatic system of the South China Sea, paleo-SST reconstruction for this region may provide valuable opportunities for exploring the relationship between the Asian monsoon and ENSO.

6.3. Decadal Variations

[25] In order to quantify the decadal SST variations in the Pacific region, harmonic analysis was performed on the coral Sr data from this study and the previously published Rarotonga coral Sr/Ca data [*Linsley et al.*, 2000b] using the SPECTRUM analysis program. This technique is based on the Lomb-Scargle Fourier transform combined with the Welch-Overlapped-Segment-Averaging procedure. A detailed description of its paleoclimatic application is given by *Schulz and Stattegger* [1997]. Because of the anthropogenic disturbance in the period 1973–1975 (see above), the harmonic analysis was carried out on the continuous Sr record from 1906 to 1972 for the Xisha coral. The results show that the annual signal is dominant (not displayed), but also reveal a 26-year secondary cycle and weaker cycles of 13 years and 5.4 years (Figure 6). It is noteworthy that the 13-year cycle appears to be independent of the 26-year cycle because the 13-year cycle does not disappear when the 26-year cycle is subtracted for the harmonic analysis. The harmonic spectrum of the Rarotonga coral Sr/Ca record [*Linsley et al.*, 2000b] also shows that one year is the dominant cycle (not displayed), 26 years is a secondary cycle, and 5.7 years is a weak cycle (Figure 6).

[26] The 26-year cycle appears as a dominant cycle for both Xisha and Rarotonga, revealing a decadal SST change in the Pacific Ocean. This oscillation has been previously identified as a robust, recurring pattern of ocean-atmosphere

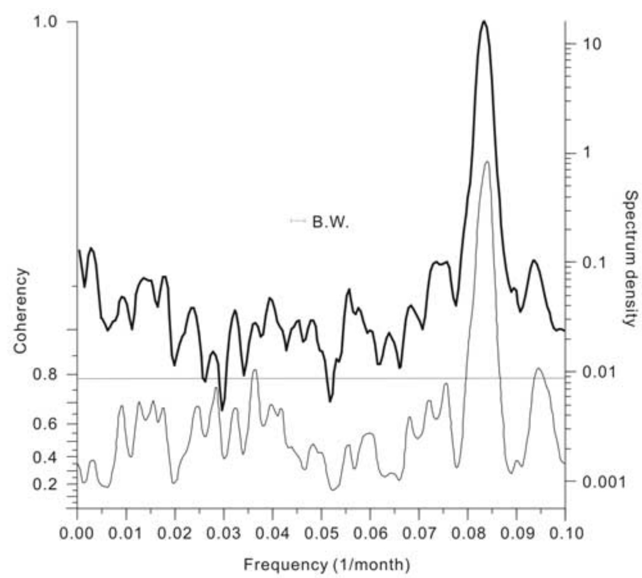

Figure 7. Cross-spectrum (heavy line) and coherency spectrum (light line) of the Xisha coral Sr and the Rarotonga coral Sr/Ca data. The bar represents band width (BW). The dash line for the coherency spectrum is provided with a 5% significance level. The degree of freedom is 6.

climate variability in the North Pacific [*Latif and Barnett*, 1994; *Mantua et al.*, 1997; *Minobe*, 1999; *Gershunov et al.*, 1999]. The 13-year cycle is weak for the Xisha coral Sr data, and is below the 95% false alarm level of the harmonic analysis for the Rarotonga coral Sr/Ca record. This cycle has been widely observed in coral δ^{18}O records for the North Pacific [*Cole et al.*, 1993; *Cobb et al.*, 2001; *Linsley et al.*, 2000a; *Urban et al.*, 2000]. As an important periodic change, this cycle is believed to be associated with the contribution and/or response of ENSO event to decadal-scale variability in the subtropical Pacific [*Gu and Philander*, 1997; *Zhang et al.*, 1997; *Guilderson and Schrag*, 1998; *Zhang et al.*, 1998].

[27] The 5–6 year cycle is weak for both the Sr and the Sr/Ca data, but it is consistent with the typical pace of ENSO resulted from inter-annual interaction of air-sea in the equatorial and tropical Pacific [*Trenberth*, 1976; *Barnett*, 1991]. This indicates that ENSO recurrence can be recorded by corals from subtropical Pacific regions.

[28] In order to examine the coherency of the reconstructed SST time series for the SCS and Rarotonga, cross-spectrum analysis was conducted for the two sets of data using Dynamics Optimization methods. A detailed description of this technique is given by *Yu and Ding* [1998]. The results show a highly coherent 1-year cycle for the Xisha coral Sr data and the Rarotonga coral Sr/Ca data (Figure 7), with a phase difference of 3.6 months for the Sr data from Xisha lagging the Sr/Ca record from Rarotonga. These results are consistent with the response of the Northern and Southern Hemispheres to the natural seasonal variations. In contrast, the variabilities on inter-annual and decadal scales are not coherent for the Xisha Sr data and the Rarotonga Sr/Ca data (Figure 7), implying the existence of different climate mechanisms for the two regions. The South China Sea region is closely linked to tropical and subtropical Pacific conditions channeled through the two contrasting seasonal Asian monsoons. The interannual- and decadal-scale SST variabilities of the Xisha coral Sr data may be related to significant interaction of the ocean-atmosphere-land system. In contrast, Rarotonga is located in the South Pacific gyre and the interannual- and decadal-scale SST variabilities are likely only related to interactions of the ocean-atmosphere system [*Linsley et al.*, 2000b].

7. Conclusions

[29] A coral Sr thermometer has been established for a *Porites* coral from Xisha Island, and the SST record was reconstructed for the period 1906 to 1994. The reconstructed SST data show that the late 20th century was warmer (about 1°C) than the early 20th century, and that two cooling and three warming shifts occurred in the century. The prolonged warming event from the 1960s to present is striking. These results are consistent with previous studies using instrument-measured data and employing other proxies, showing that our coral Sr thermometer is a high fidelity recorder of past SST in the region.

[30] Synchronous but opposite SST variations for the South China Sea and the South Pacific are revealed by comparison of the Xisha Sr data with the previously published Rarotonga Sr/Ca data. This study also demonstrates consistent SST variations for the South China Sea and equatorial west Pacific. Therefore our data from the SCS can be used in a broader context.

[31] Time series analysis shows a 26-year cycle for both the South and North Pacific, and a 13-year cycle for the North Pacific. Cross-spectrum analysis indicates that similar decadal cycles may not necessarily be caused by the same climatic mechanisms.

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T. Lee, Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan.

B. Nie, South China Sea Institute of Oceanography, Chinese Academy of Sciences, Guangzhou, China.

M. Sun and Y. Sun, Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong, China. (minsun@hkucc.hku.hk)

G. Wei, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China.

Z. Yu, College of Mineral Resource and Environment Sciences, China University of Mining and Technology, Beijing, China.