Variations in the Pacific Decadal Oscillation since 1853 in a coral record from the northern South China Sea

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Received 16 November 2012; revised 24 March 2013; accepted 25 March 2013; published 9 May 2013.

[1] The Pacific Decadal Oscillation (PDO) has been shown to have significant climatic and environmental impacts across the Pan-Pacific Basin; however, there are no records of PDO activity from the South China Sea (SCS), the largest marginal sea in the northwest Pacific Ocean. This study suggests that a series of geochemical profiles obtained from a modern coral in the northern SCS records annual PDO activity dating back to 1853. These geochemical data are significantly correlated with the PDO index, and their patterns of variation closely match those of the PDO index over the last century. The relationship between the PDO and coral geochemistry may be related to the influence of the PDO on rainfall on Hainan Island. Rainfall patterns influence the volume of terrestrial runoff, which, in turn, is a primary determinant of $\delta^{18}O$ and $\Delta\delta^{18}O$ values in coral; however, coral $\delta^{13}C$ values are also influenced by the ^{13}C Suess effect. The results indicate that Sr/Ca ratios in coral are affected by a combination of sea surface temperature and terrestrial runoff.

Citation: Deng, W., G. Wei, L. Xie, T. Ke, Z. Wang, T. Zeng, and Y. Liu (2013), Variations in the Pacific Decadal Oscillation since 1853 in a coral record from the northern South China Sea, *J. Geophys. Res. Oceans*, *118*, 2358–2366, doi:10.1002/jgrc.20180.

1. Introduction

[2] The Pacific Decadal Oscillation (PDO) is a pattern of interdecadal climate variability in the North Pacific Basin, defined by the leading empirical orthogonal function (EOF) of the monthly anomalies of sea surface temperature (SST) in the Pacific poleward of 20°N [*Mantua et al*., 1997; *Mantua and Hare*, 2002]. The PDO, or the closely related Interdecadal Pacific Oscillation (IPO) [*Power et al*., 1999a; *Folland et al*., 2002], has a widespread influence on surface climate, including temperature and precipitation anomalies in the Pan-Pacific Basin [e.g., *Power et al*., 1999a, 1999b; *Salinger et al*., 2001; *Mantua and Hare*, 2002; *Gordon and Giulivi*, 2004; *Yuan and Miyamoto*, 2004; *Yang and Zhu*, 2008; *Australian Bureau of Meteorology and CSIRO*, 2011; *Mao et al*., 2011; *Cai and van Rensch*, 2012].

[3] As the largest marginal sea in the northwest Pacific Ocean, the South China Sea (SCS) should also be affected by the PDO; however, no previous research has documented PDO activity from the SCS. The only record of past PDO activity from the western side of the Pacific basin is from adjacent continental areas of eastern China, and this record is based on proxies of summer rainfall (an historical drought/flood index) derived from Chinese historical documents [*Shen et al*., 2006].

[4] Data from a recent study in the Ogasawara Islands, Japan, suggests that during the last century, coral Sr/Ca and U/Ca ratios were closely correlated with the instrumental PDO index, and therefore may record PDO variations in the extratropical North Pacific [*Felis et al*., 2010]. Several studies have also demonstrated that certain geochemical proxies, such as the Sr/Ca ratio and $\delta^{18}O$ values, can reflect the long-term behavior of the IPO; these proxy records extend to periods prior to the availability of instrument readings [*Linsley et al*., 2000a; *Evans et al*., 2001; *Linsley et al*., 2008].

[5] Coral reefs are widely distributed across the SCS, and their geochemical signatures have been frequently used as proxies for reconstructing past climate changes in this region [*Yu*, 2012], including those related to the activity of the East Asian monsoon and El Niño during the Holocene [e.g., *Sun et al*., 2005; *Wei et al*., 2007]. In this study, we present an approximately 159 year annually resolved record of coral geochemical proxies ($\delta^{13}C$, $\delta^{18}O$, and Sr/Ca) from the northern SCS. By analyzing the relationship of these geochemical records to the PDO index, the potential for geochemical signatures will be considered to act as proxies for PDO activity in the SCS.

2. Materials and Methods

[6] In April 2011, a long core was collected from a *Porites lutea* colony living at a water depth of about 4 m on a fringing reef at Longwan, Qionghai, 2 km off the east coast of Hainan Island in the northern SCS (19°17′11.94″N, 110°39′21.06″E) (Figure 1). The coral core was first sectioned into slices 1 cm thick and 5–7 cm

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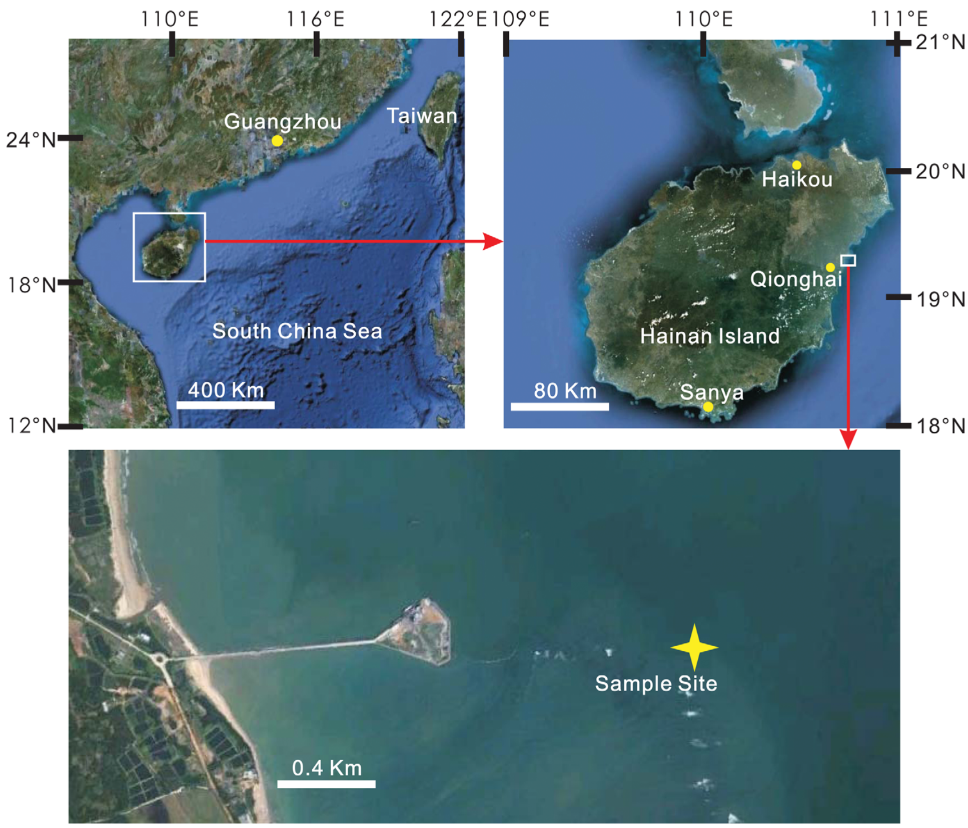

Figure 1. Satellite image of Hainan Island. Yellow star indicates the sample location.

wide. Then, X-ray photographs were taken to reveal the regular and well-defined annual density bands, which were used to establish the coral chronology. Next, the coral slices were soaked in 10% H_2O_2 for 24 h to remove organic matter, followed by ultrasonic cleaning in deionized water for 30 min to remove surface contaminates [*Wei et al.*, 2007]. Samples were collected at annual intervals along the main growth axis using a digitally controlled milling machine. The annual sampling frequency was adequate for the purpose of this study, which mainly focuses on long-term changes over multidecadal scales. X-ray diffraction (XRD) analyses of the samples showed that the coral skeleton was 100% aragonite. Scanning electron microscopy (SEM) imaging revealed that there was no secondary aragonite present in the coral skeleton.

[7] Coral skeletal δ^{13}C and δ^{18}O analyses were performed using a GV Isoprime II stable isotope ratio mass spectrometer (IRMS) coupled with a MultiPrep carbonate device that used 102% H_3PO_4 at 90°C to extract CO_2 from the coral samples, following the procedures described by *Deng et al*. [2009]; the IRMS was located at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China. Isotope data were normalized to the Vienna Pee Dee Belemnite (V-PDB) using the NBS-19 standard (δ^{13}C = 1.95‰, δ^{18}O = –2.20‰). Multiple measurements on this standard yielded a reproducibility of 0.03‰ for δ^{13}C and 0.06‰ for δ^{18}O. Replicate measurements were made on ~15% of the samples.

[8] Analyses of Sr/Ca ratios were conducted on a Varian Vista Pro inductively coupled plasma atomic emission spectrometer, in the same laboratory as that used for the stable isotope measurements. Replicate analyses of a coral standard solution showed excellent reproducibility, with an external precision of 0.16%. See *Wei et al*. [2007] for a more detailed description of the Sr/Ca methodology.

[9] Coral $\Delta\delta^{18}$O, a coral proxy for precipitation in the northern SCS [*Shen et al*., 2005; *Deng et al*., 2009], was calculated by subtracting the SST contribution from the coral δ^{18}O values [*Gagan et al*., 1998], according to

$$\Delta\delta^{18}\mathrm{O} = \mathrm{d}\,\delta^{18}\mathrm{O}/\mathrm{d}T \times \left[T_{\delta 18\mathrm{O}} - T_{\mathrm{Sr/Ca}}\right],$$

where dδ^{18}O/dT is the slope of the empirical δ^{18}O–SST function reported by *Song et al*. 2006, and $T_{\delta 18O}$ and $T_{Sr/Ca}$ are the apparent SSTs calculated from δ^{18}O values and Sr/Ca ratios, respectively. We used the Sr/Ca-SST relationship reported by *Liu et al*. [2006].

[10] For comparison with coral geochemical records, the averages of the leading principal component (PC) of the monthly January-February-March SST anomalies in the North Pacific Ocean poleward of 20°N (from the University of Washington's Joint Institute for the Study of the Atmosphere, and Oceans, http://jisao.washington.edu/pdo/PDO.latest) were used to establish the PDO index after 1900 [*Mantua et al*., 1997].

[11] To identify low-frequency cycles of the PDO recorded in the coral records, a red-noise spectral analysis

was performed on the geochemical data from the coral and the instrumental PDO index time series using the program REDFIT [*Schulz and Mudelsee*, 2002]. To remove the high-frequency signals in the time series, low-pass filtering with a cutoff frequency of 13 years was performed using Paleontological Statistics (PAST) software [*Hammer et al.*, 2001].

3. Results and Discussion

3.1. PDO Signals in Coral Time Series

[12] The δ^{13}C, δ^{18}O, $\Delta\delta^{18}$O, and Sr/Ca coral time series data for the SCS coral are presented in Figure 2. To remove the local high-frequency variability in the geochemical signatures and to highlight the signal thought to be related to PDO activity over decadal-to-interdecadal time scales, we applied a 3 year running average to all time series. Over the entire duration of the coral record (from 1853 to the present), the smoothed geochemical profiles match the instrumental PDO index remarkably well (Figure 2), and all except the coral Sr/Ca ratio are significantly correlated with the PDO index (Table 1). Because our results are based on only a single coral record, the correlation coefficients associated with the PDO index are somewhat low, which is similar to the results of *Felis et al*. [2010]. However, as coral proxies generally show excellent reproducibility, reliable climate records can be generated from a single coral core [*Stephans et al*., 2004]. The broad correlations between the geochemical records of this coral and the PDO index indicate that the strong low-frequency components of the PDO preserved within the geochemical record are trustworthy and reliable.

[13] Instrumental observations are sparse prior to 1950, and thus the quality of the PDO index derived for the early decades of the 1900s is relatively low. To validate the correlations between the PDO index and the coral time series in this study, we examined the correlations between our geochemical records of the SCS coral and those from corals in the Pacific, which are believed to record Pacific decadal variability [*Holland et al*., 2007]. We obtained the Pacific data from the World Data Center website (http://www.ngdc.noaa.gov/paleo/paleo.html) and chose all available δ^{18}O values from the Pacific sites to use in our comparisons. The Pacific coral δ^{18}O data were transformed to annual resolution by averaging the monthly and seasonal values for each year. The data were then compared with the annual-resolution coral δ^{18}O values obtained in this study. The results indicate that SCS coral δ^{18}O values are significantly correlated with most Pacific coral records, except those from Tarawa and Secas (Table 2). On this basis, we conclude that the correlations between the PDO index and the coral time series data in this study are reliable and that coral records from the SCS could provide much longer records for PDO activity in this region, given samples with longer durations.

[14] The results of the red-noise spectral analysis also suggest the presence of interdecadal cycles in the SCS, with periods of ~12, 15, 18, 35, and 53 years, as well as interannual cycles with periods of ~2–4 years. Similarly, the PDO index also shows interdecadal periodicities of ~37 years and interannual periodicities of 3 and 4 years (Figure 3). A direct comparison of the coral time series data with the PDO index gives statistically significant correlations at interdecadal time scales (Figure 2 and Table 1). During the 20th century, the PDO exhibits two general periodicities: one of the order of 15–25 years and the other of the order of 50–70 years [*Mantua and Hare*, 2002]. Therefore, the interdecadal cycles preserved within the coral time series data in the SCS are in good agreement with periodicities of PDO variability typical in the North Pacific.

[15] While statistically significant, the correlations between the PDO index and the coral indices are not very robust, as described earlier. Meanwhile, the spectral analyses show a common interannual periodicity (2–4 years) for all the indices. This may indicate that the components of the interannual periodicities have not been sufficiently removed by the method of averaging (3 year running averages). To diminish the contribution of the interannual variability to the correlations between the PDO index and the coral indices, a low-pass filter with a 13 year cutoff was applied to the indices, except in the case of the Sr/Ca ratio. The results show that after low-pass filtering, all of the time series nearly covary with the PDO index (Figure 4), and the correlations between the coral records and PDO index are significantly improved (Tables 1 and 3). Therefore, the interannual cycles apparently may not contribute a lot to the correlations between the PDO index and the coral indices. The interannual signals probably record the signature of quasibiennial and El Niño-Southern Oscillation (ENSO) signals, as the interannual variability in the SCS is remotely influenced by ENSO [*Liu et al*., 2004; *Wang et al*., 2006; *Liu et al*., 2011]. The presence of ENSO signals in the SCS has also been suggested by patterns of high-resolution time series data (spanning the last century) from modern SCS corals [*Peng et al*., 2003; *Sun et al*., 2004; *Chiang et al*., 2010].

[16] The decadal variability in SCS coral records can also be compared with the IPO index (1871–2005), which is represented by January-February-March temperature anomalies after low-pass filtering with a 13 year cutoff and can be regarded as the quasi-symmetric of the PDO [*Power et al*., 1999a; *Folland et al*., 2002]. The correlations between some low-pass filtered coral indices (δ^{13}C and $\Delta\delta^{18}$O) and the IPO index are statistically significant (Table 2), and the covariations between them are slightly weaker than those between the coral time series data and the PDO index after low-pass filtering (Figure 5). Notably, both the correlations and the covariations between the IPO index and the low-pass filtered PDO index are excellent (Table 2 and Figure 5), which may validate that the IPO can be regarded as the quasi-symmetric Pacific-wide manifestation of the PDO [*Folland et al*., 2002].

[17] Decadal-interdecadal variability is popular in both tropical and midlatitude Pacific regions, and its physical mechanisms cannot be explained by simple statistical tools [*Wang and Picaut*, 2004]. In the tropical Pacific, decadal-interdecadal patterns are similar to those of ENSO patterns [*Zhang et al*., 1997; *Luo and Yamagata*, 2001], and in the North Pacific, at least four decadal modes have been identified [*Luo and Yamagata*, 2002]. The possible physical mechanisms for explaining Pacific decadal variability can be divided into three broad categories: (1) a combination of tropical-extratropical interactions, (2) pure tropical

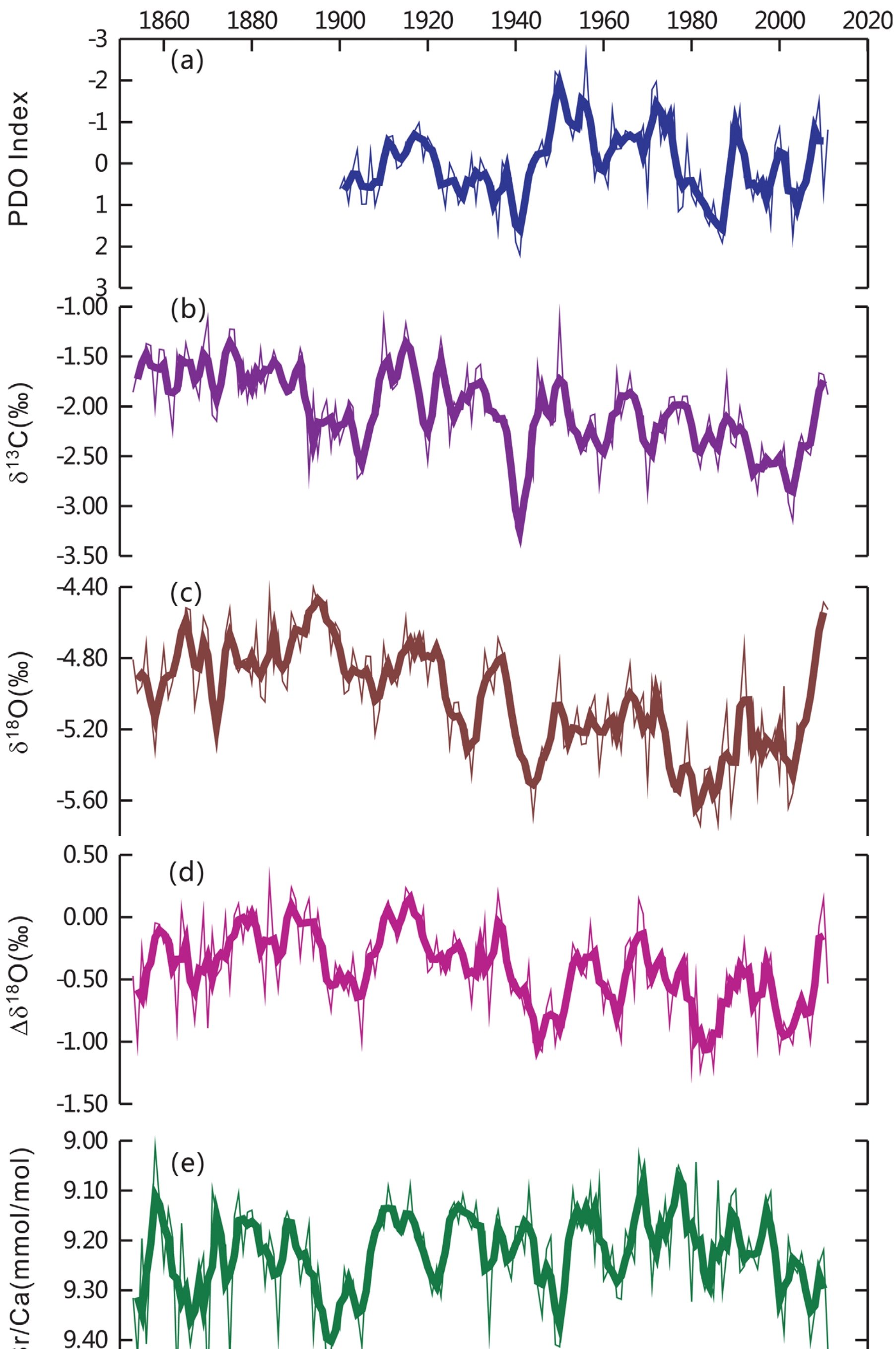

Figure 2. (a) Time series of the Pacific Decadal Oscillation (PDO) index calculated by averaging the monthly January-February-March SST anomalies since 1900 in the North Pacific Ocean poleward of 20°N (data from the University of Washington Joint Institute for the Study of the Atmosphere and Oceans, http://jisao.washington.edu/pdo/PDO.latest) [*Mantua et al*., 1997]. Time series of the (b) annually resolved coral δ^{13}C record, (c) coral δ^{18}O record, (d) coral $\Delta\delta^{18}$O record calculated by subtracting the SST contribution from the coral δ^{18}O (see text), and (e) coral Sr/Ca record. Bold lines represent 3 year running averages.

processes, and (3) pure extratropical processes [*Yeh and Kirtman*, 2005]. Given the range of possible physical mechanisms, the interdecadal signals in the SCS corals may not necessarily reveal the activity of either the PDO or the IPO but may be an imprint of decadal ENSO patterns. However, the PDO is an obvious candidate for forcing the tropical decadal variability through an atmospheric bridge [*Wang and Picaut*, 2004], and it is not related to the modulation of

ENSO amplitude and is not a residual associated with periods of either more or less active ENSO [*Yeh and Kirtman*, 2005]. Given all the available information, we suggest that the interdecadal signals in the SCS corals represent the imprints of the PDO, as the SCS is the largest marginal sea in the northwest Pacific Ocean.

3.2. Possible Effects of PDO on Corals

[18] Figure 2 and Table 1 show that all of the geochemical time series data of the coral follow similar variational patterns and that their correlations between one another are statistically significant, except for that between Sr/Ca and δ^{13}C. This indicates that the parameters are likely controlled by similar mechanisms. Trace element levels and isotopic ratios in nearshore corals are mainly controlled by river runoff and terrestrial inputs [*Furnas*, 2003; *McCulloch et al.*, 2003; *Moyer and Grottoli*, 2011; *Moyer et al.*, 2012]. As the coral sampled here was from a fringing reef, its geochemical composition may have also been influenced by river runoff and terrestrial inputs. Based on our previous studies, river runoff associated with rainfall on Hainan Island is an important influence on the chemistry of coastal seawater, including sea surface salinity, δ^{18}O, and the δ^{13}C of dissolved inorganic carbon (DIC) [*Deng et al.*, 2009; W. F. Deng, unpublished data]. Furthermore, the amount of nearshore river runoff is controlled mainly by rainfall [*Peng et al.*, 2002]. Meteorological studies suggest that the interdecadal variations in rainfall over South China are associated with the PDO [*Chan and Zhou*, 2005; *Li et al.*, 2010; *Mao et al.*, 2011]. Therefore, it seems reasonable to assume that the PDO also influences the amount of rainfall and runoff over Hainan Island in the northern SCS, and that the amount of rainfall and runoff drives the general interdecadal variability in the geochemical time series of the coral.

Table 1. Intercorrelations Between the PDO Index and Coral Geochemical Parameters[a]

	PDO Index	δ^{13}C	δ^{18}O	$\Delta\delta^{18}$O	Sr/Ca
PDO Index	–	0.000	0.003	0.014	0.418
δ^{13}C	−0.38	–	0.000	0.000	0.480
δ^{18}O	−0.26	0.55	–	0.000	0.000
$\Delta\delta^{18}$O	−0.21	0.54	0.70	–	0.000
Sr/Ca	−0.02	0.004	0.38	−0.40	–

[a]Correlation coefficients are shown in the lower left portion of the table, and corresponding p values in the upper right portion. The correlation analysis is based on 3 year running averages of data in all of the time series. For the PDO index, $n = 110$; for the coral records, $n = 157$.

[19] The warm phases of the PDO may cause positive rainfall and runoff anomalies, which deliver more freshwater onto the fringing reef. This freshwater, which is typically depleted in ^{18}O and ^{13}C but enriched in Sr, may greatly influence the composition of the seawater, and in turn, the geochemical compositions of the corals in coastal regions [*Wei et al.*, 2000; *Deng et al.*, 2009; W. F. Deng, unpublished data]. The opposite situation occurs during cool phases of the PDO. These relationships are supported by similar observed patterns of variation in, and close correlations between, the time series of the coral geochemical data and the PDO index (Table 1). Coral δ^{13}C, δ^{18}O, and $\Delta\delta^{18}$O show significant positive correlations with one another, and they are all negatively correlated with the PDO index. The positive correlations between δ^{13}C and δ^{18}O can be an indicator of early marine diagenesis in corals [*Müller et al.*, 2004; *Quinn and Taylor*, 2006], but our XRD and SEM results show no evidence of secondary mineralization; thus, this positive correlation may indicate that coral δ^{13}C and δ^{18}O values are mainly controlled by variations in the isotopic composition of seawater associated with coastal runoff, occurring over annual and decadal time scales. As a proxy for seawater δ^{18}O, the positive correlation between $\Delta\delta^{18}$O and δ^{18}O in corals suggests that coral δ^{18}O is affected mainly by the δ^{18}O of the ambient seawater, rather than temperature, as temperature changes on annual to decadal time scales are very small. The positive correlation between annually resolved coral δ^{13}C and $\Delta\delta^{18}$O series is similar to results from Sanya on the south coast of Hainan Island, where the monthly coral δ^{13}C and $\Delta\delta^{18}$O values are positively correlated and controlled by river runoff (W. F. Deng, unpublished data). Therefore, the interannual and interdecadal variations of coral δ^{13}C, δ^{18}O, and $\Delta\delta^{18}$O appear mainly controlled by the amount of rainfall and associated runoff, which is influenced by the PDO.

[20] The observation that coral Sr/Ca ratios are not significantly correlated with the PDO index, as are the other time series data, suggests that this ratio is controlled by multiple factors (Table 1). The positive correlation between Sr/Ca and δ^{18}O and the negative correlation between Sr/Ca and $\Delta\delta^{18}$O may indicate that both temperature and the Sr/

Table 2. Correlations Between SCS Coral δ^{18}O Values and Those in the Pacific[a]

	Moorea[b]	PNG[c]	Amedee[d]	Nauru[e]	Tarawa[f]	Secas[g]	Palmyra[h]	Clipperton[i]
SCS (this study)	$n = 139$	$n = 110$	$n = 140$	$n = 99$	$n = 97$	$n = 132$	$n = 113$	$n = 100$
	$r = 0.44$	$r = 0.50$	$r = 0.31$	$r = 0.60$	$r = 0.08$	$r = 0.07$	$r = 0.35$	$r = 0.30$
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.218$	$p = 0.213$	$p = 0.000$	$p = 0.001$

[a]The Pacific data are from the World Data Center website (http://www.ngdc.noaa.gov/paleo/paleo.html) and the corresponding study sites refer to those in *Holland et al.* [2007, Figure 1]. These data were transformed to annual resolution by averaging monthly or seasonal values for each year. Data sources are indicated in subsequent footnotes.
[b]*Boiseau et al.* [1999]
[c]PNG represents Papua New Guinea, *Tudhope et al.* [2001]
[d]*Quinn et al.* [1998]
[e]*Guilderson and Schrag* [1999]
[f]*Cole et al.* [1993]
[g]*Linsley et al.* [1994]
[h]*Cobb et al.* [2001]
[i]*Linsley et al.* [2000b].

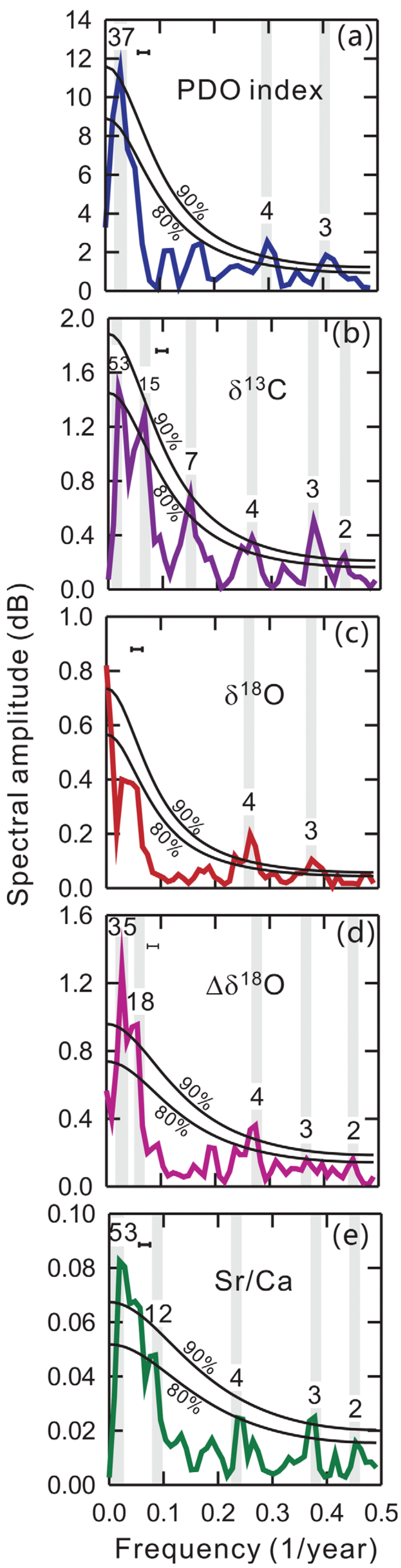

Figure 3. Results of a red-noise spectral analysis of the (a) PDO index and the records for (b) coral δ^{13}C, (c) δ^{18}O, (d) $\Delta\delta^{18}$O, and (e) Sr/Ca. The 80% and 90% significance levels are indicated. The horizontal bars indicate the bandwidths. The coral records are the same as those shown in Figure 2.

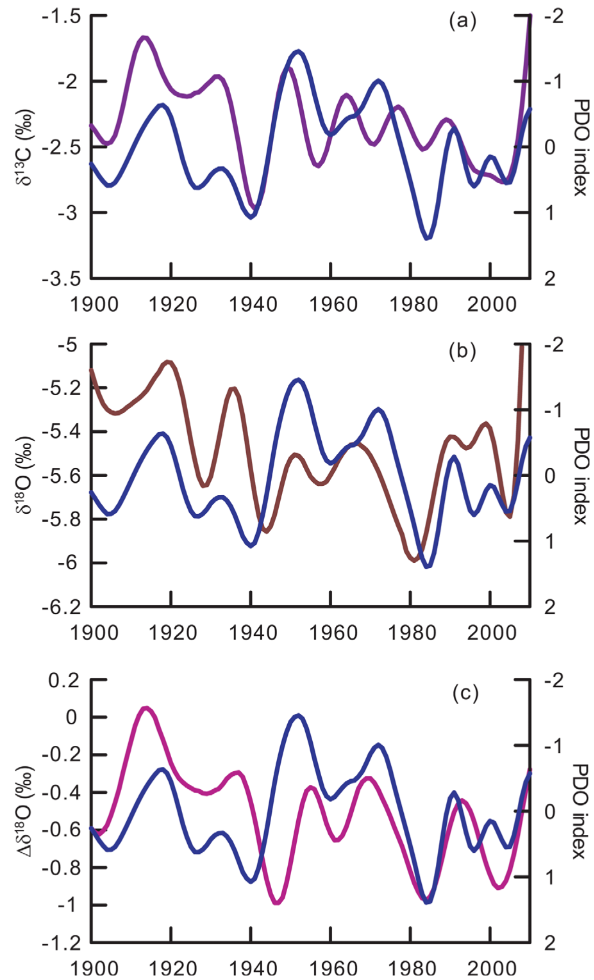

Figure 4. Low-pass filtered PDO index and coral record time series. (a) Coral δ^{13}C and PDO index, (b) coral δ^{18}O and PDO index, and (c) coral $\Delta\delta^{18}$O and PDO index. The blue lines represent the PDO index and the lines of other colors represent the coral records.

Table 3. Intercorrelations Between the IPO Index, the PDO Index, and the Low-Pass Filtered Coral Geochemical Parameters[a]

	IPO Index	PDO Index	δ^{13}C	δ^{18}O	$\Delta\delta^{18}$O
IPO Index	–	0.000	0.000	0.024	0.002
PDO Index	0.89	–	0.000	0.001	0.003
δ^{13}C	−0.39	−0.43	–	–	–
δ^{18}O	−0.17	−0.30	–	–	–
$\Delta\delta^{18}$O	−0.24	−0.26	–	–	–

[a]Correlation coefficients are shown in the lower left portion of the table, and the corresponding p values in the upper right portion. The coral time series and the PDO index are low-pass filtered using a 13 year cutoff. For the IPO index, $n = 135$; for the PDO index, $n = 112$; and for the coral records, $n = 159$.

Ca ratio of ambient seawater affect the Sr/Ca ratios in coral. The correlation between coral Sr/Ca and the PDO index is weak; however, as a proxy of SST, long-term variations in Sr/Ca still closely match those of the PDO

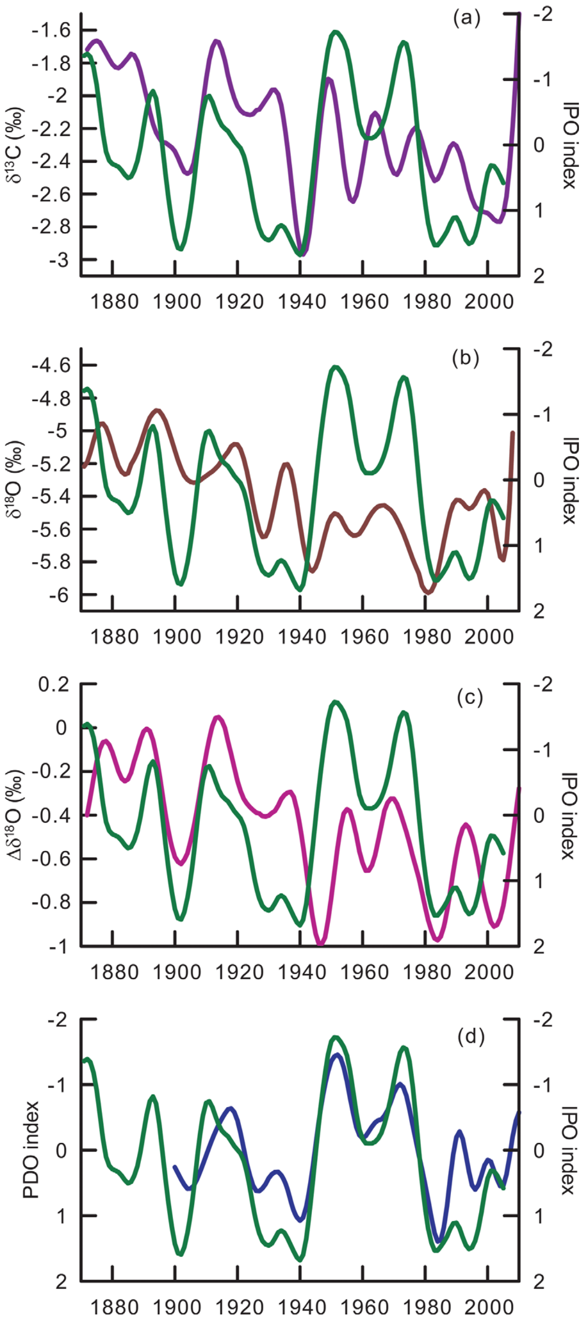

Figure 5. Low-pass filtered coral records, IPO index, and PDO index time series. The coral records are the same as those shown in Figure 4. The IPO index (1871–2005) is represented by the January-February-March temperature anomalies which have been low-pass filtered using a 13 year cutoff [*Power et al.*, 1999a]. (a) Coral δ^{13}C and the IPO index, (b) coral δ^{18}O and the IPO index, (c) coral $\Delta\delta^{18}$O and the IPO index, and (d) the PDO and IPO indices. The green lines represent the IPO index and the lines of other colors represent the coral records and the PDO index.

(Figures 2a and 2e). Relatively high Sr/Ca values (cool SSTs in the SCS) tend to coincide with warm phases of the PDO, and vice versa, which is in agreement with previous studies [*Mantua and Hare*, 2002; *Felis et al.*, 2010]. The Sr/Ca values vary in the range 9.011–9.506 mmol/mol; this wide range (0.495 mmol/mol) corresponds to an SST difference of approximately 8.0°C, as estimated from the average sensitivity of Sr/Ca to SST, which is 0.062 mmol/mol/°C [*Gagan et al.*, 2000]. Instrumental records indicate that the range in the annual SST since 1960 is approximately 1.3°C at Qinglan Harbor Meteorological Observatory, 35 km from our sample site. This implies that a range of approximately 8.0°C is a spurious temperature signal, and may result from the addition of terrestrial Sr from river runoff. This influence of runoff may weaken the correlation between the coral Sr/Ca ratio and the PDO index. It is notable that the coral δ^{13}C records show a continuously decreasing trend since 1853, which suggests that coral δ^{13}C is also influenced by the ^{13}C Suess effect [*Swart et al.*, 2010]. Both coral Sr/Ca and δ^{13}C values are affected by river runoff associated with rainfall, but this long-term decrease in δ^{13}C as a result of the ^{13}C Suess effect weakens their correlation.

4. Conclusions

[21] Variability in the PDO over the northern SCS (northwest Pacific Ocean) since 1853 was revealed in the annually resolved geochemical records of a coral from Hainan Island in the northern SCS. The geochemical signature of the corals appears to be influenced by the interdecadal variability of terrestrial runoff associated with rainfall; moreover, these low-frequency variations are likely initiated by PDO activity. Values of coral δ^{18}O and $\Delta\delta^{18}$O are mainly controlled by terrestrial runoff; however, coral Sr/Ca ratios are also affected by the SST of ambient seawater, and coral δ^{13}C values are influenced by the ^{13}C Suess effect over long time scales.

[22] **Acknowledgments.** The authors would like to thank the Editor Chunzai Wang and two anonymous reviewers for their helpful comments and constructive suggestions. Thanks also go to Aaron Stallard for improving the English of the manuscript. This work was financially supported by the National Basic Research Program of China (2009CB421206, 2013CB956103) and the National Natural Sciences Foundation of China (40902050, 40830852, 41173004). The Pacific coral data are from the World Data Center website (http://www.ngdc.noaa.gov/paleo/paleo.html). This is contribution IS-1654 from GIGCAS.

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