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Change of the ENSO-related δ^{18}O–SST correlation from coral skeletons in northern South China Sea: A possible influence from the Kuroshio Current

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ABSTRACT

Chemical proxies are useful analogs for reconstructing physical properties of sea water, such as sea surface temperature (SST) and sea surface salinity (SSS). Time series of these inferred properties would allow for reconstructions of past El Niño–Southern Oscillation (ENSO) events, where no instrumental records exist. In this study, a monthly oxygen isotope record from a *Porites* coral is used to explain how past ENSO events are recorded in the coral skeletons. The sample covers a 12 year period and was collected from Nanwan Bay, Taiwan. During El Niño events the coral skeleton is shown to produce a δ^{18}O–SST correlation with a slope of $-0.12 \pm 0.04‰\ °C^{-1}$. During other times, this value is significantly different, with a slope of $-0.21 \pm 0.04‰\ °C^{-1}$. Coral that grew during El Niño summers have δ^{18}O values which are enriched by $\sim$0.2‰, relative to other times. A possible mechanism to explain this difference may be enhanced penetration of Kuroshio Current waters into the South China Sea during summer. The observed contrast in the correlation of δ^{18}O–SST variability in this sample supports the influence of El Niño in eastern Asia.

1. Introduction

The El Niño–Southern-Oscillation (ENSO) phenomenon is well-known for its influence on regional climate and human livelihood, especially in the western Pacific Warm Pool (WPWP) and the west coast of South America. The effect of ENSO events on low-latitudes of the Pacific has been widely studied using coral records (Kuhnert et al., 1999; Le Bec et al., 2000; Cobb et al., 2003; Sun et al., 2005). During an El Niño episode, the WPWP shifts eastward and causes drought in the western Pacific regime (Morimoto et al., 2002; Cobb et al., 2003; Risk et al., 2003). Xu et al. (2004) examined the correlation between the Southern Oscillation Index (SOI) and precipitation records of 30 basins in Southeast Asia and the Pacific. They concluded that El Niño events significantly reduce precipitation in the region south of 20°N. In sub-tropical zones however, the climatic impact of ENSO cycles and the interaction between ENSO and the Asian Monsoon are still unclear. Taiwan lies on the northwestern fringe of the WPWP, and is variably influenced by both ENSO and the East Asian monsoon. East of Taiwan, the Kuroshio Current (KC), and North Equatorial Current (NEC) are the dominant surface currents and drive the heat engine in the western Pacific (Fig. 1a). Based on satellite observations and numerical modeling, these currents normally enter the northern South China Sea (NSCS) and East China Sea off the southern and northern coasts of Taiwan respectively. These currents are affected by ENSO events and exhibit seasonal variability (Kim et al., 2004; Nakamura et al., 2006; Gan et al., 2006; Yuan et al., 2006). The route and intensity of the KC control surface circulation in the NSCS area.

Corals are ideal for paleoclimatic research because of their wide distribution in tropical to sub-tropical oceans and potential geochemical tracers, such as stable isotopes and trace metals (e.g., Beck et al., 1992; Shen et al., 1996, 2005; Gagan et al., 1998, 2000; McCulloch et al., 1999; Alibert et al., 2003; Reuer et al., 2003; Wyndham et al., 2004; Sun et al., 2005). Paired Sr/Ca and δ^{18}O measurements on coral skeletons produce reliable proxy records for both sea SST and SSS (e.g., Urban et al., 2000; Tudhope et al., 2001; Cobb et al., 2003; Corrège, 2006; Abram et al., 2007). But in the early 1990s, δ^{18}O was considered to be dominated by SST, and suitable as a direct SST proxy in some tropical and subtropical regions. One reason came from the inconvenient determination of Sr/Ca ratio till the popularity of Q-ICP-MS and SF-ICP-MS in late 90s. The other was the distinct thermo-seasonality which would make the SST-induced δ^{18}O prevailed in the coral skeletons. Based on the assumption of a constant annual mean value for $\delta^{18}O_{sw}$, the first-order equation of $\delta^{18}O_{coral}$–SST relationship can be expressed as:

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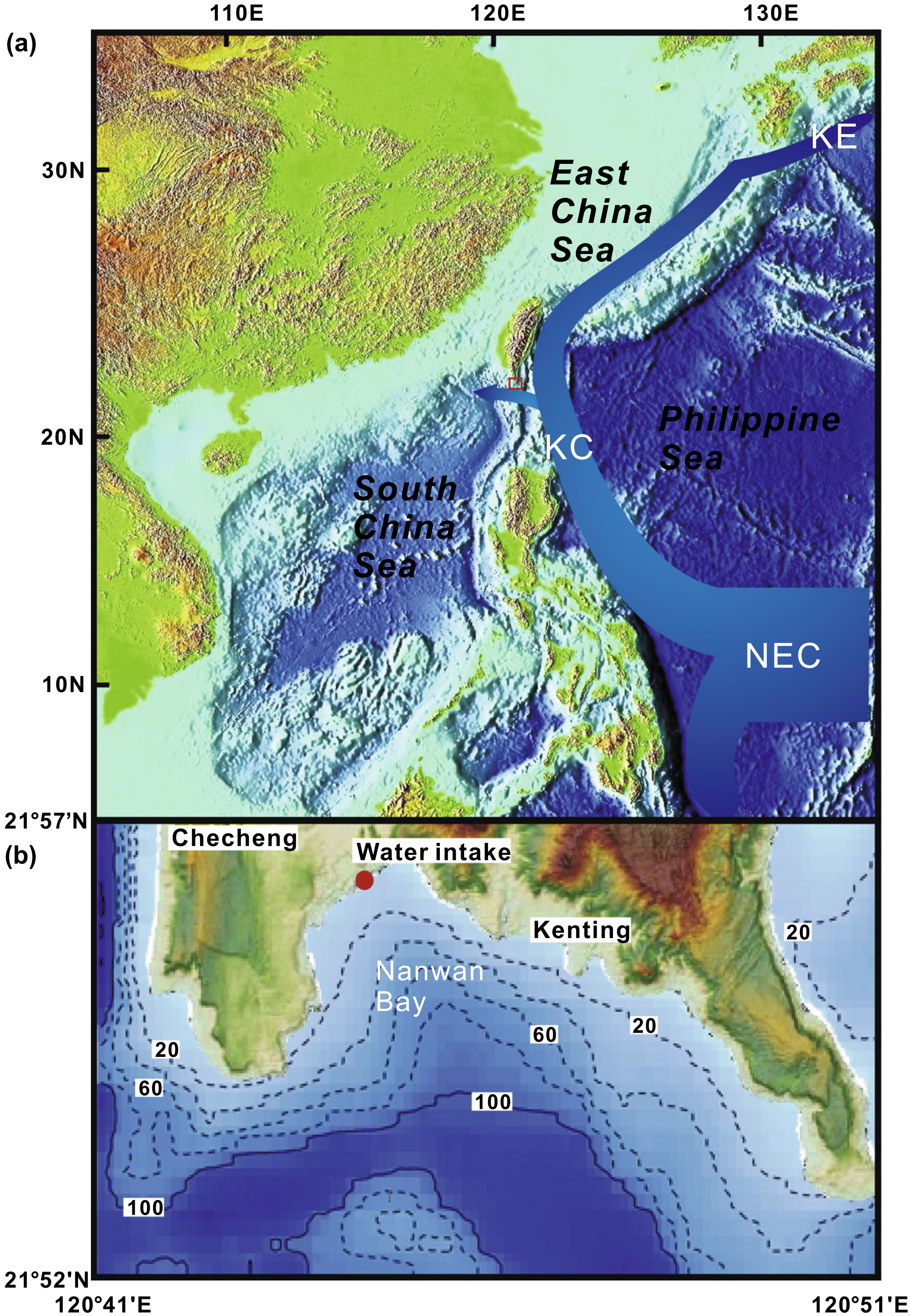

Fig. 1. (a) Geographical map of East Asia and route of the Kuroshio Current (KC, blue shadowed). The main stream of KC goes northward along east coast of Taiwan, but in the winter, a westward branch may move across the 121E longitude and penetrate into the north SCS through the Luzon Strait (Qu and Lukas, 2003; Kim et al., 2004; Qu et al., 2004). Some evidence shows the possibly ENSO-induced inter-annual pathway variations in summer season. NEC: North Equatorial Current. KE: Kuroshio Extension. (b) Geographical and bathymetrical map of southern tip of Taiwan. We collected a 12-year-old living *P. lutea* coral from the water intake pond of the Third Nuclear Power Plant at the west edge of Nanwan Bay on 1st October 2003 (shown as filled red circle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\delta^{18}O_{coral} = a + b \times SST$$

The published slopes of $\delta^{18}O_{coral}$–SST calibrations range from 0.14‰ to 0.25‰ °C^{-1} (Suzuki et al., 1999; Al-Rousan et al., 2002; Asami et al., 2004; Sun et al., 2005). The dispersion may be due to regional hydrological conditions. Shen et al. (2005) indicated the resulting sensitivity is closer to the low end of the published range when considering the variant seawater $\delta^{18}O$. In other words, the slope change must be associated with changes in a seawater property affected by climate or hydrology. Accordingly, a 12-year $\delta^{18}O$ section of living *Porites* coral collected from southern tip of Taiwan was used to examine the latent impact of ENSO and the ocean current, KC, on the coral $\delta^{18}O$–SST relationship.

2. Materials and methods

Nanwan Bay (121°E, 22°N) is located at the southern tip of Taiwan. It is semi-enclosed and its inlet is partially confined by a 60-m sill along its southern margin (Fig. 1b). Luzon Strait is located to the south, the only deep channel that connects the SCS to the Philippine Sea. Surface seawater from the Philippine Sea flows through the channel into the SCS between October and January (Centurioni et al., 2004). The mean annual SST is between 23 and 28 °C (Shen et al., 1996), with an amplitude of less than that of 11 °C (19–30 °C) at Leizhou Peninsula (Yu et al., 2005), while the two locations are only 1.5° different in latitude. This variabiity is reasonably attributed to the influence of Kuroshio Current. The average rainfall is 2000 mm year^{-1} from 1971 to 2000 according to a local Central Weather Bureau meteorological station and no major river discharges into the Nanwan Bay but localized cold seawater upwelling daily (Lee et al., 1999). The study area is situated in the southwest summer monsoon regime and more than 80% annual rainfall occurs from June to early October. A cold and dry winter season follows from October to March, while April and May are the transition.

A section of *Porites lobata* coral that grew over a 12 year period was collected at a water depth of 5 m from the intake pond of the Third Nuclear Power Plant in Nanwan Bay on 1 October 2003. The coral sample was washed with sodium hypochlorite and freshwater to eliminate organic coral tissue and endolithic algae. A 7-mm-thick slab was cut along major growth axis, cleaned with deionized water and dried at 50 °C. Subsamples were sliced at every 0.8 mm, yielding a resolution of 2–3 weeks along the maximum extension axis identified by an X-ray radiograph. Each subsample was sequentially cleaned with H_2O_2, and a reducing reagent, and polished using dilute HNO_3 (Shen et al., 2005). A Finnigan MAT Delta-^{plus} mass spectrometer, coupled with an automatic carbonate (Kiel) device, was employed to measure carbon and oxygen stable isotopic compositions. All measurements are reported relative to the Pee Dee Belemnite isotopic standard (PDB). The long-term external precision is less than 0.02‰ (1σ) for $\delta^{13}C$ and 0.06‰ (1σ) for $\delta^{18}O$ estimated from a National Taiwan University carbonate standard (MAB, a Chiukju Marble), with $\delta^{13}C$ and $\delta^{18}O$ values of 3.43‰ and −6.91‰ respectively. The accuracy was calibrated with the international carbonate standard NBS19.

3. Results and discussion

Twelve-year (1992–2003) records of monthly-resolution skeletal $\delta^{18}O$ data are illustrated in Fig. 2b and given in Table 4. The $\delta^{18}O$ mean is −5.1‰, with a range from −5.9‰ to −5.2‰ in summers and −4.9‰ to −4.2‰ in winters. $\delta^{18}O_{coral}$ values during summer El Niño periods are observed to be enriched by about 0.2‰, relative to La Ninã and normal periods. In winter seasons $\delta^{18}O_{coral}$ during El Niño and La Ninã values are depleted by about 0.1‰, relative to normal conditions.

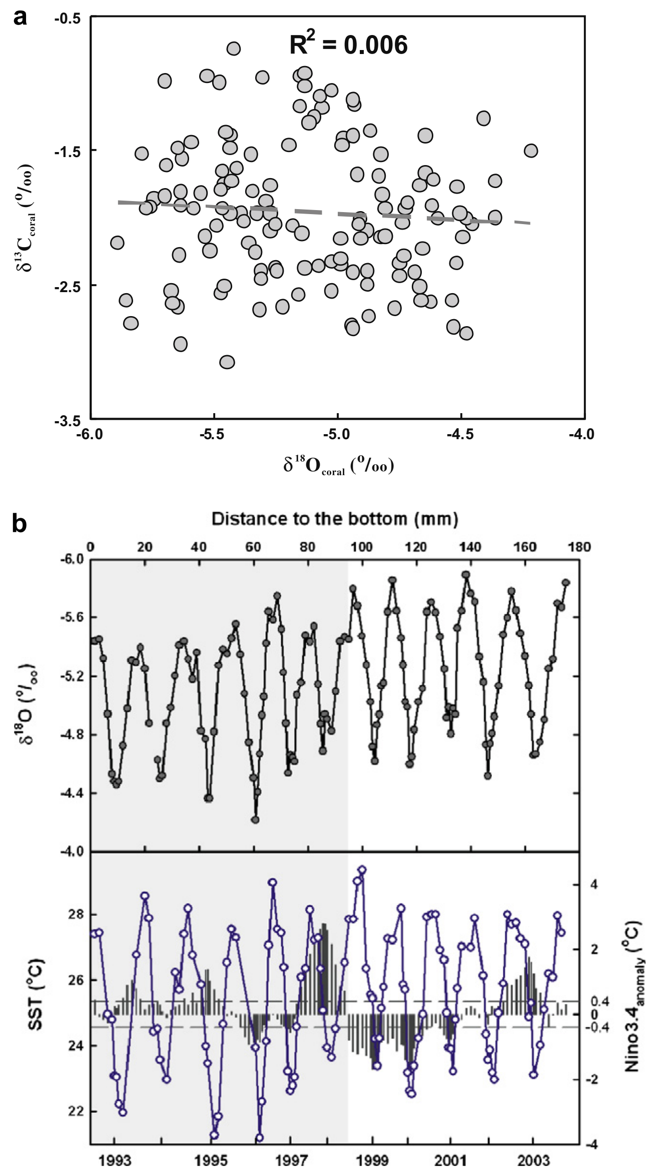

Fig. 2. (a) Correlation between the $\delta^{18}O$ and $\delta^{13}C$ data (after McConnaughey, 1989). No positive correlation was shown, inferring variations of $\delta^{18}O$ did not result from a kinetic mechanism. (b) Correlation between the stratigraphic $\delta^{18}O$ and SST. Nino3.4 index was also presented (gray bars). Two time periods were shown, 1992–1998 (shadded) and mid-1998 to 2003. Dashed horizontal line indicated the ±0.4 °C threshold of El Niño and La Niña.

McConnaughey (1989) proposed two individual tests to identify kinetic effects that can affect coral skeletal $\delta^{13}C$ and $\delta^{18}O$ simultaneously by examining the correlation between $\delta^{18}O$ and $\delta^{13}C$ and a direct calculation of linear extension rate (LER). Many studies (e.g., McConnaughey, 1989; Al-Rousan et al., 2002) have shown $\delta^{18}O$ offsets away from an equilibrium state when the LER is less than 5 mm year^{-1}, or the calcification rate is less than 5 g cm^{-2} year^{-1} (McConnaughey, 1989). The LER in this Nanwan coral, of 12–17.6 mm year^{-1}, is much higher than this threshold. This fact and the lack of covariance between carbon and oxygen isotopes suggest that kinetic effects in our coral sample isotope record are negligible (Fig. 2a).

3.1. Correction of SST data

The high-spatial-resolution (4 km × 4 km) AVHRR Pathfinder dataset (Version 5.0) was utilized in this study to qualify our SST results, instead of the frequently used 1° × 1° Integrated Global Ocean Services System (IGOSS) SST data. Table 1 shows a good correlation (R^2 = 0.91) between the Pathfinder data and IGOSS data, with about 0.3 °C offset (equal to less than 0.06‰ in δ^{18}O), indicating a homogeneous SST distribution and no local differences in our sample collection area. The on-site instrumental SST data are available only from May 2002 to October 2004, courtesy of the National Museum of Marine Biology and Aquarium (NMMBA). A strong correlation (R^2 = 0.87) was found between the Pathfinder data and on-site NMMBA data (Table 1); however, a significant 1.5 °C offset over the 30-month course. This high SST from the satellite-based data could be attributed to its accuracy limitation. To correct the offset, an equation was applied to the raw Pathfinder data.

$$SST_c = SST_r - 1.52$$

In this equation, SST_r represents the raw data and SST_c is the corrected data. The Pathfinder SSTs were corrected with this offset to describe the Nanwan thermal condition and used to establish the apparent δ^{18}O–SST regressions in 1992–2003.

3.2. Relationships between δ^{18}O and SST

In order to compare coral δ^{18}O and instrumental records, an inter-annual chronology was developed based on seasonal variations in δ^{18}O. We correlated δ^{18}O with the NASA/NOAA satellite SST records of 1992–2003 (National Oceanographic Data Center, 4 km AVHRR Pathfinder Version 5.0). To obtain the best-fitting δ^{18}O–SST calibration in any given year, the maximum δ^{18}O value was matched with the minimum SST value and the minimum δ^{18}O value was matched with the maximum SST value. Coral δ^{18}O results between the maximum and minimum values were interpolated linearly to match with SST records. Individual ^{230}Th dates with ≦1 year precision by Shen et al. (2008) were also used to confirm that no matching errors resulted from temporary growth hiatuses.

Table 1
Correlations of different SST data sets.

	NMMBA SST	Pathfinder SST	IGOSS SST
Correlation coefficient among the various SST data sets after fitting to 1:1 line			
NMMBA SST		0.87	0.87
Pathfinder SST	0.87		0.91
IGOSS SST	0.87	0.91	
Offsets among the different SST data sets after fitting to 1:1 line			
	Pathfinder SST	IGOSS SST	
NMMBA SST	−1.52	−0.98	
Pathfinder SST		−0.32	

Offset values are obtained using column-direction as the *x*-axis while row-direction as the *y*-axis.

Table 2
Slopes and correlation coefficients between $\delta^{18}O_{coral}$ and SST regressions for each year from 1992 to 2003.

Year	Regression equation	R^2	Number of points
1992	$y = -0.24x + 1.13$	0.90	5
1993	$y = -0.11x - 2.14$	0.66	9
1994	$y = -0.15x - 1.10$	0.60	9
1995	$y = -0.10x - 2.74$	0.27	7
1996	$y = -0.14x - 1.72$	0.73	9
1997	$y = -0.15x - 1.17$	0.69	11
1998	$y = -0.15x - 1.22$	0.70	11
1999	$y = -0.18x - 0.53$	0.68	11
2000	$y = -0.18x - 0.53$	0.96	12
2001	$y = -0.25x + 1.15$	0.80	10
2002	$y = -0.18x - 0.67$	0.84	12
2003	$y = -0.24x + 0.90$	0.96	7

Year-by-year regressions of coral δ^{18}O–SST from July 1992 to September 2003 are given in Table 2. The slope ranges from −0.10 to −0.25‰ °C^{-1}. The averaged regression slope of −0.14‰ °C^{-1} in 1993–1998 is significantly different from the value of −0.24‰ °C^{-1} in 1992 and −0.20‰ °C^{-1} in 1999–2003 (two tailed *t*-test at 5% probability level). The δ^{18}O–SST regressions during El Niño events, La Ninã events and normal years are given in Fig. 3a. The slope of −0.12 ± 0.04‰ °C^{-1} during El Niño events is significant lower than −0.21 ± 0.04‰ °C^{-1} under normal conditions (Table 3). The slope during La Niña events, −0.16 ± 0.04‰ °C^{-1}, is slightly lower than that of normal condition. An interesting result observed from these values is that smaller slopes in δ^{18}O–SST regressions are associated with relatively lower correlation coefficient values (R^2). Taken together, the gentler δ^{18}O–SST slope and lower R^2 values imply a weakening of the thermal component in coral δ^{18}O correlation, i.e. the increased influence from other hydrological factors.

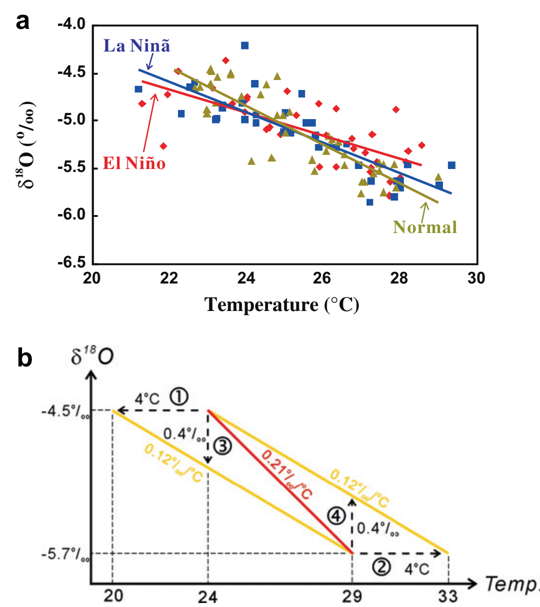

Fig. 3. (a) Regressions between δ^{18}O and SST under three different climate scenarios. The slope in "El Niño years" is −0.12‰ °C^{-1}, significantly different from "Normal years", −0.21‰ °C^{-1}, and "La Ninã years" has a value of −0.16‰ °C^{-1}. (b) Schematic view shows four possible paths to decrease the slope value of a known line. Two paths are related to temperature: Path 1 results from increased summer temperature, and Path 2 results form decreasing winter temperature. We can not exclude the possibility of simultaneous changes in both seasons. Paths 3 and 4 represent the calculated shift caused by seawater δ^{18}O under the assumption of invariant monthly summer and winter SST.

Table 3
Slope values ±1 standard error between $\delta^{18}O_{coral}$ and SST among different climate scenarios.

	Mean of the slope	*t* Test
El Nino	−0.12 ± 0.04	S.D.
La Niña	−0.16 ± 0.04	N.S.D
Normal	−0.21 ± 0.04	

An El Niño/La Ninã event is recognized when the 5-month running average of standardized Nino3.4 in six consecutive months is at least 0.4 °C higher/lower than the long-term average. Based on the criterion, there are five El Niño events, March 1991 to July 1992, February–September 1993, June 1994 to March 1995, April 1997 to April 1998, and May 2002 to March 2003, and two La Ninã events, September 1995 to March 1996 and July 1998 to February 200. The rest in this interval is considered as "Normal condition".

Table 4
Statistics of analyzing the latent variation in satellite-based summer/winter SST (SST_s) data and measured summer/winter $\delta^{18}O_{coral}$ ($\delta^{18}O_m$).

	SST_s in Summer	$\delta^{18}O_m$ in Summer	SST_s in Winter	$\delta^{18}O_m$ in Winter
El Niño	27.33 ± 0.72	−5.33 ± 0.26	23.21 ± 1.25	−4.77 ± 0.26
La Ninã	27.58 ± 1.00	−5.56 ± 0.20	23.40 ± 1.03	−4.75 ± 0.23
Normal	27.42 ± 0.70	−5.55 ± 0.20	23.17 ± 0.35	−4.66 ± 0.18

3.3. SST anomaly

As mentioned above, the slope of the $\delta^{18}O$–SST correlation during El Niño conditions is significantly lower than during normal conditions. Similar relations are also found between 1992–1998 and 1999–2003. Two temperature-related possibilities (paths 1 and 2 in Fig. 3b) could cause the decrease in slope for a specific regression line as follows: (1) by an increase in the summer temperature, and (2) by a decrease in winter temperature. Simultaneous change in both parameters is possible as well. According to a simple geometric calculation, the routine ~5 °C annual amplitude in SST has to increase to 9 °C when the slope changes from −0.21‰ °C^{-1} to −0.12‰ °C^{-1}. That corresponds, for the two most extreme cases, in a shift from 28 °C to 32 °C in summer or a 4 °C decline, down to 19 °C, in winter (paths 1 and 2 in Fig. 3b). Table 4 lists the comparison of average summer (JJAS) and winter (DJF) temperatures for the El Niño, La Ninã and normal periods. No difference among the summer SST was observed (27.33 °C, 27.58 °C, and 27.42 °C). On the other hand, the difference of mean SST for winter months was about 0.2 °C, which is within the amplitude of seasonal variation and corresponds to only a 0.04‰ $\delta^{18}O$ difference, less than the 1σ analytical error (0.06‰) of oxygen isotopes. Furthermore, if the winter temperature did decrease to 19 °C, close to the known survival limit for corals, an apparent metabolic response should be found from the $\delta^{13}C$ records, but it is not the case. A similar result was obtained, resulting in only a 0.1 °C difference, from calculating summer temperatures of the two time periods, 1992–1998 and 1999–2003, This is consistent with previous studies that no obvious SST anomaly can be detected in the off-equatorial area of the western Pacific during ENSO events. Hence, temperature fluctuations may not be the main reason for the $\delta^{18}O$–SST slope change.

Although summer and winter average SST values are the same for the three surface ocean circulation conditions, a broader SST distribution during the winter in both El Niño and La Ninã periods is an important feature of our results. The finding in the last paragraph of paired changes of slope values and correlation coefficient emphasize the fluctuant SST dependency. The cause is still unclear but may result from a regressive Eastern Asia winter monsoon during ENSO events (Li and Mu, 2000). This would induce an unstable climate condition, whose fluctuations are more sensitive to local events instead of the winter monsoon. This supposition could also explain why there is no consensus for the effect of a single ENSO event on Eastern Asia.

3.4. SSS anomaly

$\delta^{18}O_{coral}$ records the oxygen isotope value of seawater, which is governed by both SST and SSS. Continuous *in situ* SSS data was not available for the Nanwan site, apart from a few discontinuous CTD records available between 1992 and 2003, measured by the National Center for Ocean Research (NCOR). These records indicated less than 0.3 psu differences between summer El Niño and normal conditions, consistent with about 0.1 psu differences given in the Integrated Global Ocean Station System (IGOSS) UMD Carton goa database, while less than 0.1 psu differences between winter El Niño and normal conditions (http://ingrid.ldeo.columbia.edu/SOURCES/.UMD/.Carton/.goa/.beta7/.s/) (Fig. 4). These differences

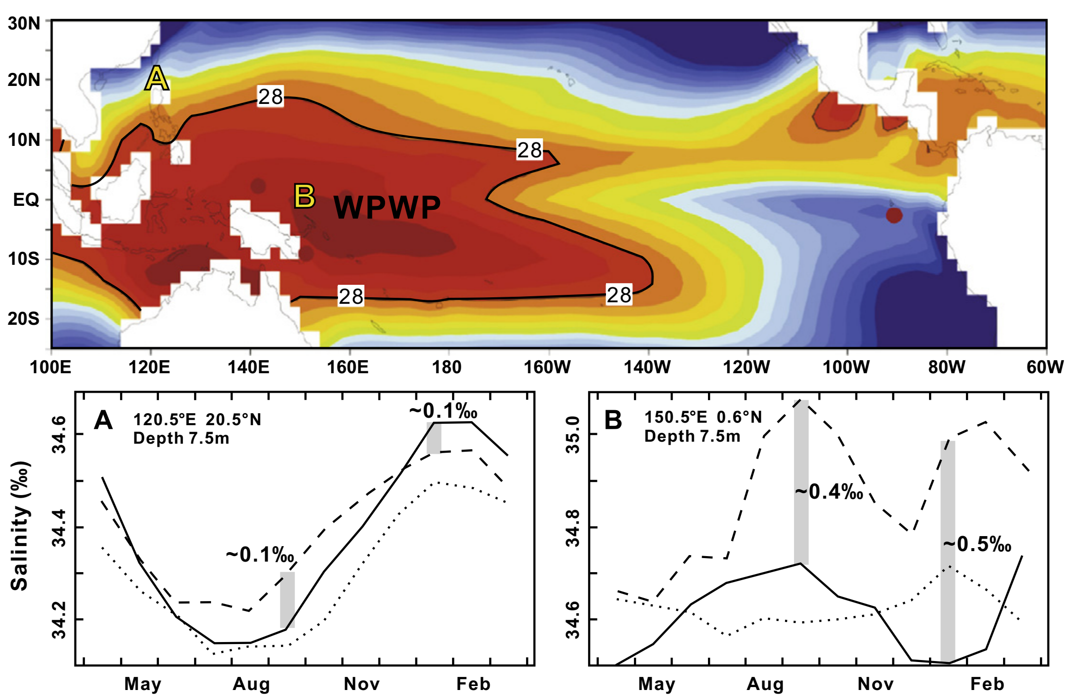

Fig. 4. Average winter (DJF) SST of the tropical Pacific Ocean in 1950–2004 from the National Center for Ocean Research (NCDC) (Smith and Reynolds, 2004). Western Pacific Warm Pool (WPWP) is figured as the 28 °C line, roughly confined in the region of 15°S–15°N in latitude and 100°E–160°W in longitude. Representatives from site A and B (A: 20.5°N, 120.5°E; B: 0.6°N, 150.5°E) display two inconsistent responses on SSS during ENSO (Carton et al., 2000). Solid line shows the normal episode, while dashed and dotted lines are the El Niño and La Ninã episode respectively. Site A, which is close to our study area, lack obvious salinity variations (~0.1‰) compared to the western tropical Pacific (0.4–0.5‰).

in SSS are too small to be useful for monitoring changes in ENSO and cannot be compared directly to out observed $\delta^{18}O_{coral}$ variations. The principal reason for this is because NCOR and IGOSS records reflect averaged and smoothed SSS values.

We also checked for local precipitation data to examine if a temporary pulse of SSS dilution could obscure the $\delta^{18}O_{coral}$–SST relationship. After subtracting the average summer precipitation from 1971 to 2000, rainfall in wet seasons during El Niño is about 560 mm less than that during normal conditions, with no difference in dry seasons. A similar amount (about 400 mm less) was obtained in the time window 1992–1998, when compared to the 1999–2003 period. According to the calculation of Shen et al. (2005), rainfall contributed up to 2.5% of the total Nanwan water, and a 560 mm precipitation decrease would cause at most a 0.1‰ decline in the $\delta^{18}O_{d\text{-}w}$ value ($\delta^{18}O_{d\text{-}w}$ indicating $\delta^{18}O$ difference between dry and wet seasons). Under the assumption of steady $\delta^{18}O_{sw}$ in dry seasons, the oxygen isotope value in wet seasons (summer) is expected to be enriched by 0.1‰. Moreover, given nearly constant solar radiation of about 275 ± 75 MJ m^{-2} during 1991–2003, the evaporation effect would be the same during normal and ENSO conditions. This result is reached by excluding very high values, more than 450 MJ m^{-2} in June 1991 to August 1992 and June–September 2003, recorded at a local meteorological station 10 km from our study site. We conclude that salinity fluctuation cannot entirely explain the increasing $\delta^{18}O_{coral}$ values during El Niño conditions.

3.5. Mechanism for ENSO-related $\delta^{18}O_{coral}$ anomaly

As outlined above, we did see different $\delta^{18}O$–SST relationships between El Niño and normal years. Given the constant SST/SSS during El Niño and La Ninã periods shown above, what mechanism could account for the inter-annual $\delta^{18}O_{coral}$ variability? We propose that the "Kuroshio contribution" explains the increased $\delta^{18}O_{coral}$ values. Many studies have demonstrated that both monsoonal winds and ENSO activity could determine the position of the NEC bifurcation point, which controls the transport of the KC (Qu and Lukas, 2003; Kim et al., 2004; Qu et al., 2004). On a seasonal scale, the northeast winter monsoon generates a cyclonic ocean circulation, which shifts the NEC bifurcation northward (Qu and Lukas, 2003) and reduces the Kuroshio transport (KT) east of Luzon (Masumoto and Yamagata, 1991; Tozuka et al., 2002; Yaremchuk and Qu, 2004). When the KT approaches its seasonal minimum in winter, water from the Philippine Sea penetrates more easily into the SCS through the Luzon Strait, causing Luzon Strait transport (LST) toward its seasonal maximum (Yaremchuk and Qu, 2004). The situation in summer is reversed when the southwest monsoon prevails. On an inter-annual scale, the northward shift of the NEC bifurcation corresponds to a weaker KT during El Niño years (Masumoto and Yamagata, 1991; Tozuka et al., 2002), thus providing a favorable condition for Pacific waters to penetrate into the SCS through the Luzon Strait, similar to the winter condition. The situation is reversed during La Niña years (Yaremchuk and Qu, 2004). Thus, as El Niño events occurred over summer, an "unusual summer Kuroshio penetration" might be found, although the influence of inter-annual variability is believed to be secondary to the seasonal cycle of volume transport driven by monsoonal winds (Kim et al., 2004).

Lin (2000) analyzed water samples collected around the northern SCS and Luzon Strait from April 1998 to April 1999. The average $\delta^{18}O$ value of Kuroshio surface water was measured as 0.25‰ (maximum value of 0.42‰) and that of SCS surface water as −0.20‰ to 0.20‰ with an average of −0.05‰. Shen et al. (2005) used the term "upwelled water (UW)" to describe the seawater ascending from a depth of 100–200 m, which is actually a mixture of SCS and KC. The estimated contribution of the UW is ca. 75% of the surface seawater in Nanwan. The difference between these two water masses was about 0.3–0.5‰, and caused a 0.2–0.4‰ shift in the $\delta^{18}O_{sw}$ value at Nanwan in different mixtures of SCS and KC waters. This perfectly matches the $\delta^{18}O_{coral}$ difference observed for El Niño and normal conditions, ~0.2‰. Thus, we believe that the Kuroshio influence is likely responsible for the observed

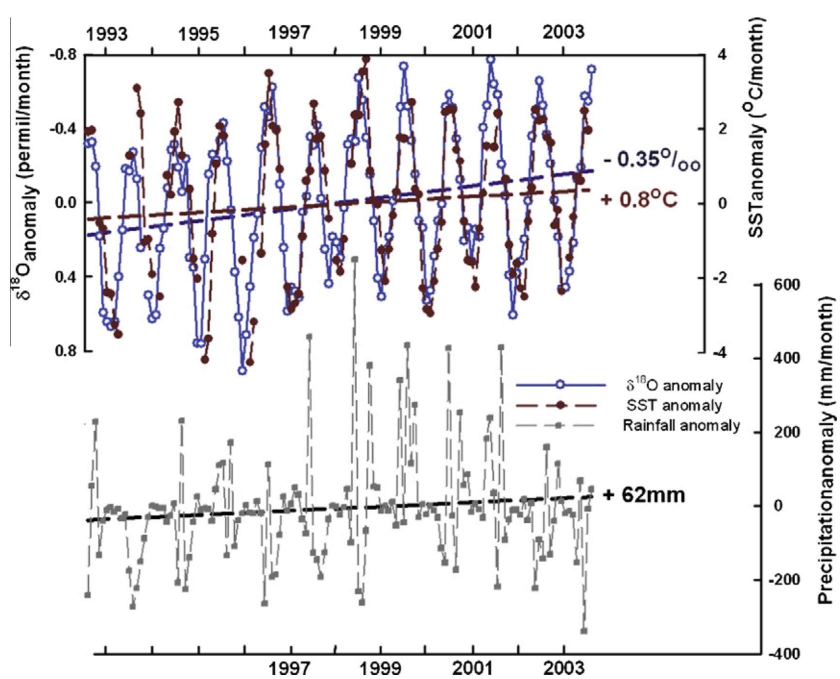

Fig. 5. Long-term trend in Nanwan Bay. Three proxies, $\delta^{18}O_{coral}$, SST, and precipitation, were compared. Even including both of the effect from SST and precipitation, the $\delta^{18}O_{coral}$ decrease still could not be entirely accounted for, suggesting the existence of at least one more environmental factor that is concordant with the conclusion of annual correlation.

δ^{18}O–SST relationship when an El Niño event occurs. The amplitude of this effect may be expected to be more pronounced during summer than in winter. Another observation described below supports our hypothesis. By the wavelet analysis of two Kuroshio indicators from 1984 to 2004, Nakamura et al. (2006) demonstrated that the Kuroshio meanders in Tokara Strait was modulated by inter-annual variations. The variance amplitude of the Kuroshio meanders during 1993–1998 and small during 1999–2003, which positively correlated to KC volume transport. It is coincident with the period of gentler δ^{18}O–SST slope, $-0.14‰\,°C^{-1}$ in our study. Thus, the intensity and route of the KC obviously influences the hydrology of the western sub-tropical Pacific and it is also the most important heat-transporter in western Pacific. This process would conceivably be strengthened during glacial periods because the Luzon Strait is believed to have been the only opening of the semi-closed SCS basin.

3.6. The trend of $\delta^{18}O_{coral}$ in Nanwan coral

Shen et al. (2005) showed that *Porites* corals from the semi-opened bay could be used to quantitatively reconstruct SST and SSS records by coupled Sr/Ca and δ^{18}O analyses. They concluded that three end members exist at this site: (1) upwelled water, (2) offshore surface water, and (3) fresh water, providing 73–75%, 24.5–25%, and 0–2.5% of the annual $\delta^{18}O_{sw}$ variation respectively. In this study we have shown that the δ^{18}O records from these coral skeletons also shed light on inter-annual ENSO-related KC fluctuations. During the 12-year period studied here, the $\delta^{18}O_{coral}$ decreased 0.35‰, the SST increased 0.8 °C, and precipitation increased about 60 mm month^{-1} (Fig. 5). If using $-0.18‰\,°C^{-1}$ as the slope for the δ^{18}O–SST regression (Shen et al., 2005), the 0.8 °C rise in SST would induce a 0.15‰ reduction in $\delta^{18}O_{coral}$. Another 0.1‰ lightening would be expected to result from local precipitation (Shen et al., 2005). Thus, at least 0.1‰ of the total 0.35‰ decrease in $\delta^{18}O_{coral}$ is attributed to changes in Nanwan seawater inputs, with summer pulses of KC water entering between 1992 and 1998. Up to 0.2‰ could be attributed to this mechanism, if we ignore local precipitation. From 1993 to 1998, three El Niño events occurred, more often than the following consecutive 5 years. Although only five months data in 1992 were analyzed, a change in the δ^{18}O–SST relation still can be recognized. The 6-year interval (perhaps as long as 8 years) was consistent with the known 3–7 year ENSO periodicity. In summary, the observed increases in SST and precipitation recorded by instruments can explain part of the δ^{18}O trend in coral skeletons, tending towards lighter values, but at least one third of the bulk δ^{18}O shift in coral records a KC signal that crosses 121°E longitude. The changing nature of ocean currents through time is difficult to quantify, but this study demonstrates how δ^{18}O coral records can be applied generally in the East Asian Subtropics.

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