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Sea surface temperature variations in the southwestern South China Sea over the past 160 ka

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Abstract

Sea surface temperatures (SSTs) in the southwestern South China Sea have been reconstructed for the past 160 ka using the U^{k}_{37} paleothermometer from the core MD01 - 2392. The temperature differences between glacial times (MISs 6 and 2) and interglacial times (MISs 5.5 and 1) are 2.2 ~ 2.5 ℃. Younger Dryas event during the last deglaciation was documented in both the planktonic foraminiferal $\delta^{18}O$ and SST records. After MIS 5.5, SSTs displayed a progressive cooling from 28.6 to 24.5 ℃, culminating at the LGM. During this gradual cooling period, warm events such as MISs 5.3, 5.1 and 3 were also clearly documented. By comparison of SST between the study core and Core 17954, a pattern of low or no meridional SST gradients during the interglacial periods and high meridional SST gradients during the glacial periods was exhibited. This pattern indicates the much stronger East Asian winter monsoon at the glacial than at the interglacial periods. Spectral analysis gives two prominent cycles: 41 and 23 ka, with the former more pronounced, suggesting that SSTs in the southern SCS varied in concert with high-latitude processes through the connection of East Asian winter monsoon.

Key words: sea surface temperature, alkenone, Late Quaternary, South China Sea, East Asian monsoon

1 Introduction

The South China Sea (SCS), located between the East Asian continent and the western Pacific, has attracted many researchers in paleoceanography in the last decades. Its attractiveness lies in its environmental sensitivity to the East Asian monsoon system (Wang, 1999) and glacial/interglacial sea level changes (Pelejero, Kienast et al., 1999). Owing to closeness to the equator and the western Pacific warm pool (WPWP), the southern part of the sea and its adjacent lands has a tropical climate with only small seasonal changes. Paleoevironmental reconstructions in the southern SCS thus can give clues to the stability of the WPWP during glacial/interglacial cycles and the significance of tropical area in the global climate change.

The U^{k}_{37} index has been successfully and widely used for reconstructing Late Quaternary SST changes in the global oceans (e.g., Bard et al., 1997; Ohkouchi et al., 1994). In the SCS, SST reconstructions by means of foraminiferal transfer functions have been addressed since the 1980s (Wang and Wang, 1990) but SST estimates based on the U^{k}_{37} in-

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dex have been applied only in recent several years (Huang et al., 1997; Pelejero, Grimalt et al., 1999). The advantage of the U_{37}^{k} method is that the index is free from bias originating from the partial dissolution of calcareous tests, which often alter SST estimates on the basis of the faunal abundance of planktonic foraminifera (Miao et al., 1994). In addition, the technology requires small amounts of sample (usually less than 3 g dry sediments) and can give SST estimates with an error less than 0.5 ℃ (Villanueva et al., 1997), which is suitable for high-resolution paleoceanographic studies. The present work gives the results of high-resolution SST reconstructions in the southwestern SCS over the past 160 ka by means of the C_{37}-alkenone-derived U_{37}^{k} index paleothermometer.

2 Materials and methods

The present study is based on a deep-sea core (MD01 - 2392) of undisturbed sediments from the southwest SCS (9°51.13′N, 110°12.64′E; Fig. 1). The core was collected at the water depth of 1 966 m during the IMAGES Ⅶ cruise of WEPAMA in May 2001.

A total of 134 samples were analyzed at 10 or 20 cm intervals for the upper 20 m of the core. The time resolution ranged from 0.4 to 2.4 ka and averages 1.1 ka, with a higher resolution for the upper 8 m. The procedures used for U_{37}^{k} index determinations are described elsewhere (Villanueva et al., 1997). Briefly, sediment samples were freeze-dried and manually ground for homogeneity. Then the samples were extracted with dichloromethane three times. The extracts were hydrolyzed with 6% potassium hydroxide in methanol. The hexane extracts from the alkaline solution were then fractionated by silica column chromatography to separate hydrocarbons and ketones from the polar fraction. After derivatization with bis (trimethylsilyl) trifluoroacetamide

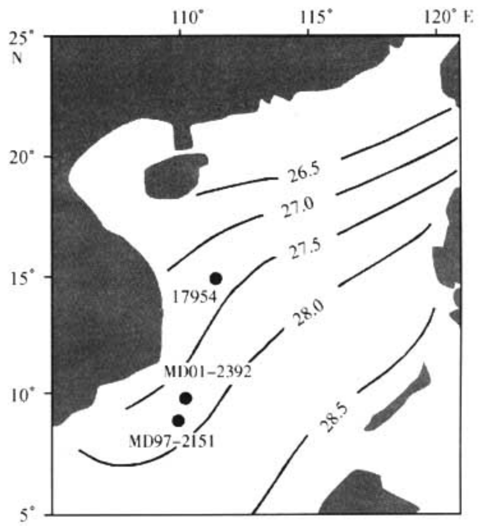

Fig. 1. Location of Cores MD01 - 2392, MD97 - 2151 and 17954 discussed in the text. The contour lines show the annual SST (℃) distributions in the SCS, which are obtained from NODC (Levitus) *World Ocean Atlas* (http://www.cdc.noaa.gov).

(BSTFA), the extracts were analyzed by gas chromatography (HP5890) with a flame ionization detector.

The U_{37}^{k} index (I) is defined as the fraction of diunsaturated C_{37} alkenone in the total of C_{37} alkenones, the sum of di- and triunsaturated C_{37} alkenones. In the SCS, calibration of U_{37}^{k} in sediment core tops versus SST (θ) showed a good linear relationship ($r = 0.964$) for the annually averaged 0 ~ 30 m SST, resulting in the equation $I = 0.031 \times \theta + 0.092$ (Pelejero and Grimalt, 1997). We use this equation for paleo - SST reconstructions in this paper.

3 Chronostratigraphy of the core

The chronostratigraphy of Core MD01 - 2392 is based on the comparison of its Oxygen isotope ($\delta^{18}O$) values of planktonic *Globigerinoides ruber* with those of *Globigerinoides sacculifer* of the nearby core MD97 - 2151 (8°43. 68′N, 109° 52. 14′ E; Figs 1 and 2). In addition, radiocarbon dating and a few biostratigraphic, geomagnetic and tephrochronologic markers were employed to enhance the reliability and resolution of the age model (see Fig. 1; Lee et al., 1999). The upper 20 m of Core MD01 - 2392 covers a history of about 160 ka, corresponding to the last six marine isotope stages (Fig. 2).

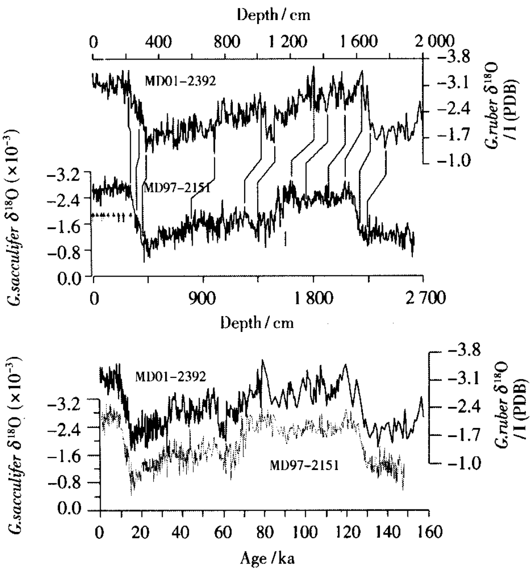

Fig. 2. Comparison and correlation of planktonic $\delta^{18}O$ values of Core MD01 - 2392 (from *Globigerinoides ruber*) with those of Core MD97 - 2151 (from *Globigerinoides sacculifer*). The correlation points are indicated by polylines between $\delta^{18}O$-depth curves. AMS C - 14 control points in Core MD97 - 2151 are indicated by arrows. The bar at the depth of 1 556 cm indicates the Toba ash (71 ka) detected.

4 Results and discussion

4. 1 SST variations over the past 160 ka

As a general trend, the U^k_{37} - SST signal shows a glacial/interglacial pattern in Core MD01 - 2392 (Fig. 3). The rises in the mean temperature from MIS 6 to MIS 5. 5 and from MIS 2 to MIS 1 (the Holocene) were 2. 5 and 2. 2 ℃, respectively. The temperature differences between last glacial maximum (LGM) and present are -3 ℃, which is consistent with previous studies (Wang et al., 1999; Huang et al., 1997) and higher than those from the western tropical Pacific (- 1. 5 ℃) (Ohkouchi et al., 1994), displaying the amplifying effect on climate signals of the marginal sea (Wang, 1999). Temperatures during MIS 5. 5 were relatively stable and showed - 1 ℃ warmer than those of the Holocene. Since MIS 5. 5, SSTs displayed a progressive cooling from 28. 6 to 24. 5 ℃, culminating at the LGM. During this gradual cooling period, warm events such as MISs 5. 3, 5. 1 and 3 were also clearly documented. The SST record during MIS 3 shows large amplitude (as large as 2 ℃) and high frequency of variations, which is similar to the millennial-scale Mg/Ca SST variability on the order of 1 to 1. 5 ℃ found in the nearby Sulu Sea (Dannenmann et al., 2003).

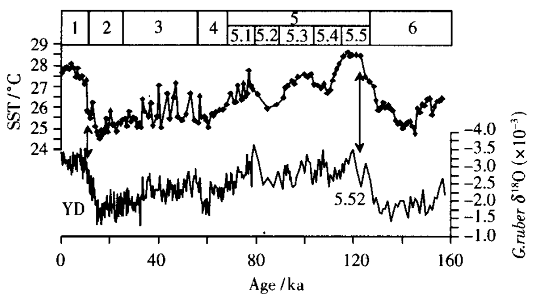

Fig. 3. Alkenone SST reconstructions from Core MD01 - 2392 for the past 160 ka.

The last deglaciation was characterized by an obvious, brief SST drop in the warming course, which was also displayed in the planktonic $\delta^{18}O$ curve (Fig. 3). This characteristic displayed in both records confirms a climate reversal event, which is most probably the well-known Younger Dryas (YD) event. This event, originally identified in high latitudes and later found to be worldwide (Kudrass et al., 1991) displayed − 0.7 ℃ drop in temperature in our U_{37}^{k} − SST records. However, during the penultimate deglaciation, the YD-type signal was not shown in the U_{37}^{k} − SST and $\delta^{18}O_{ruber}$ records, which might be resulted from the low resolution of the two proxies during this interval. Because the YD-type signal has been identified in some tropical areas (Oppo et al., 2001), further work based on high-resolution studies is needed to elucidate whether it occurred in the southern SCS.

The event MIS 5.52, which has ever been thought to be the YD-type signal by Sarnthein and Tiedermann (1990), is clearly displayed in the $\delta^{18}O_{ruber}$ record, but not in the SST data at the core MD 01 − 2392 (see Fig. 3). This phenomenon has been noticed by Pelejero, Grimalt et al. (1999) from the central SCS Core 17954 (see Fig. 1). In the northern SCS, MIS 5.52 has been found concurrent with a prominent temperature drop (Tu et al., 2000). Because the planktonic $\delta^{18}O$ was determined by the global ice volume, ambient SST of plankton, and local freshwater budget and/or $\delta^{18}O$ (Jia et al., 2006; and references therein), the MIS 5.52 event with no concurrent SST drop in Core MD01 − 2392 could be interpreted to reflect changes in the local freshwater budget and/or freshwater $\delta^{18}O$. Thus high-resolution SST reconstructions in the SCS for the period from MIS 6 to MIS 5 are urgently needed to determine the existence of some established millennial oscillations in the north Atlantic (such as cold events 19 ~ 27 pointed out by Heusser and Oppo, 2003), stability of MIS 5.5 (Cortijo et al., 2000), and evolution of the penultimate deglaciation (Oppo et al., 2001).

4.2 Changes in meridional SST gradient over the climatic cycles

In the modern SCS, the trends of the winter SST contours parallel to the South China coastal line when the northeast monsoon prevails, and the trends of summer SST contours parallel to the east Vietnam coastal line when the southwest monsoon prevails (Fig. 4). Thus the meridional SST gradients are nearly vanished from the central to the south SCS during summer. Consequently, the changes in the meridional SST gradient, i.e., the north—south contrast in temperature, give us clues to the East Asian winter monsoon variability over the past glacial/interglacial cycles.

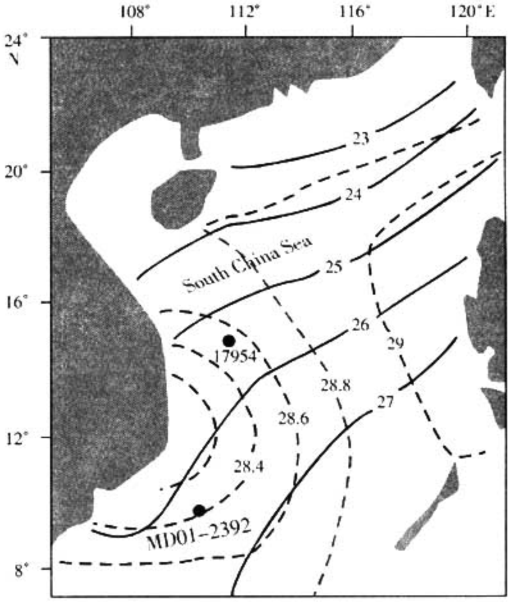

Fig. 4. Winter (December to February; solid lines) and summer (July to September; dashed lines) mean SST (℃) distributions in the SCS. Data are obtained from NODC (Levitus) *World Ocean Atlas* (http://www.cdc.noaa.gov).

Here we compare our U_{37}^{k} − SST records with those of Core 17954 given by Pelejero, Grimalt et al. (1999). Core 17954 (14°47.8′N, 111°31.5′E, 1 520 m depth) is located 5°N to our study core (see Figs 1 and 4). Thus U_{37}^{k} − SST differences between the two cores are suitable to exploring the meridional SST gradient over the past climatic cycles.

Presently, the annual SST difference between the two cores is − 0.5 ℃, with a winter difference of − 1 ℃ (higher value on the south site) and a summer difference of less than 0. 2 ℃ (slightly higher value on the north site) (see Fig. 4). Over the past 160 ka, the U^k_{37} − SST differences between the two sites fluctuated with higher amplitude than present seasonal SST differences (Fig 5). For example, during most of the glacial times, the annual SST differences were higher than 1 ℃, and even higher than 2 ℃ during LGM, which means that winter monsoon was much stronger during those periods. While during interglacial times, the differences were mostly lower than 1 ℃, and remarkably, the gradient disappeared between the two sites during MIS 5. 5. This indicates a relatively weaker winter monsoon during interglacial times.

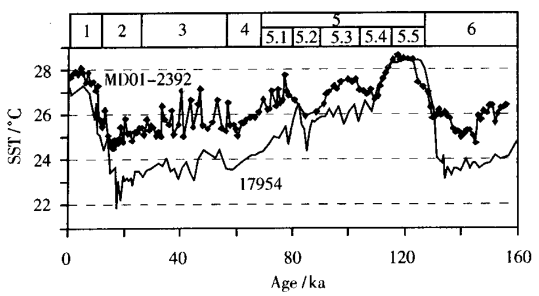

Fig. 5. Comparison of reconstructed SST from Core MD01 − 2392 with that from Core 17954. The suggested meridional SST differences in the SCS were obviously larger during the glacials than during the interglacials.

4. 3 Spectral analysis

Records of tropical SST have been found to exhibit cycles of 23 ka (orbital precession) and 100 ka (orbital eccentricity) during the past 0. 5 Ma (Rostek et al. , 1997), whereas high-latitudes SST records display much more pronounced obliquity cycles at a period of about 41 ka (Ruddiman and McIntyre, 1984). For example, Late Pleistocene SSTs in the North Atlantic displayed a meridional pattern with relatively more 41 ka power at high latitudes, and more 23 ka power at low latitudes (Ruddiman and McIntyre, 1984). Thus, 41 ka rhythms are believed to be a "polar" signal (Liu and Herbert, 2004), although the strong 41 ka power is still present in some tropical areas (Clemens et al. , 1991; Beaufort et al. , 2001). Here we give results of spectral analysis of our reconstructed SSTs of Core MD 01 − 2392.

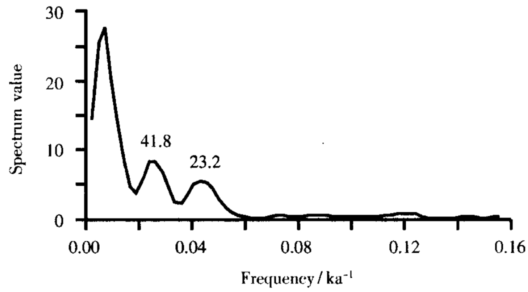

Fig. 6. Results of spectral analysis for the reconstructed SSTs from Core MD01 − 2392.

The spectral analysis was based on the program of SPECTRUM (Schulz and Stattegger, 1997). Parameters were set as follows during the analysis: 0. 05 for level of confidence; "hanning" for window type; 2 for segment; and 4 for oversampling factor. The results are schematically in Fig. 6. As can be seen, 41 and 23 ka powers are predominant in SST records. The more pronounced 41 ka power suggests that SSTs in the southern SCS varied in concert with high-latitudes processes, although the study site is located in the tropical area. Therefore, a remote connection between high latitudes and the southern SCS must account for the SST signals detected. We think this connection could be the prevailing East Asian winter monsoon, originating from high latitudes. Nevertheless, the pronounced 23 ka power tells us that tropical processes is one of the main factors that modulate the SST variations in the tropical SCS.

5 Conclusions

SST reconstructions based on the U^k_{37} index in the tropical SCS show a glacial/interglacial pattern, with glacial—interglacial differences in the range of 2.2 ~ 2.5 ℃. During the last deglaciation, The Younger Dryas event was documented in both $\delta^{18}O_{ruber}$ and SST records, with a SST drop of about 0.7 ℃. But the YD-type event in the penultimate deglaciation was not shown perhaps due to the low time resolution of this study. 41 and 23 ka spectral powers are prominent in the SST records, with the former more pronounced, suggesting that SSTs in the southern SCS varied in concert with high-latitudes processes. This teleconnection could be the winter monsoon winds that prevail in the East Asia, and originated from the high latitudes. Both temporal (from glacial to interglacial times) and spatial (comparison with Core 17954) differences in SSTs confirm a stronger northeast winter monsoon during glacial times than during interglacial times.

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