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Stepwise paleoceanographic changes during the last deglaciation in the southern South China Sea: Records of stable isotope and microfossils *

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Abstract Quantitative analyses of microfossils and stable isotopic analysis were carried out for Core SCS-12 in the southwestern slope of the South China Sea (SCS). A high-resolution paleoceanographic record for the last 13 ka was revealed with the AMS ^{14}C dates. The southern SCS has experienced stepwise paleoceanographic changes since the last deglaciation. The oxygen isotopic stage 1/2 boundary around 12.05 ka B.P. and the end of the last deglaciation around 7.70 ka B.P. are two rapid change periods (corresponding to the termination I_A and termination I_B, respectively), in between is a slow change period. The authors infer that the sea level stood at -110 m before the termination I_A, roughly the same as today after the termination I_B, and about -50 m in between. Subsequently, the average winter sea surface temperature and salinity obviously increased while paleo-productivity decreased since 12.05 ka B.P. The early Holocene $CaCO_3$ preservation spike, coupled with a high abundance of pteropoda and $CaCO_3$ content, occurred around 7.70 ka B.P.

Keywords: last deglaciation, stepwise change, stable isotope, microfossils, South China Sea.

The last deglaciation was initiated around 15 ka B.P. and ended about 7 ka B.P., lasting for 7—8 thousand years[1]. Within this short period, the continental ice sheets of nearly 3 000 m thick in the Northern Hemisphere melt and then disappeared; the sea level of the world oceans rose about 100 m correspondingly; the $\delta^{18}O$ composition of sea water became depleted; the atmospheric CO_2 content increased by about 1/3. How did the series of environmental changes happen, straight or stepwise, or even with returns in between[1]? Investigation of the processes and mechanism responsible for the last deglaciation would help us to understand the environmental system on the earth, and to provide the proper estimation and prediction for the future global changes.

The South China Sea (SCS) is an ideal marine regime for high-resolution studies on the deglacial paleoceanography because of its high sedimentation rate and extensive carbonate sediments. In the last few years, the response of sea and land to the last deglaciation has been the subject of many studies from the SCS. But most of them were concentrated on the northern basin[2,3], only a few on the southern part[4]. In fact, the southern SCS has one of the broadest shelves in the world, where during the deglacial sea level rise the sudden open of sea channels and/or abrupt increase of sea surface would have induced sudden environmental changes[5]. For example, during the last deglaciation, the amplitude of shoreline shift could reach 900 km in the

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southern SCS, with an average of at least 0.3 m per day. If the intermediate pauses and even returns are considered, the shoreline possibly had ever retreated at a speed of 1 m per day. This kind of catastrophic environment should have played an important effect on the East Asian monsoonal climate and the living environment of animal and plant, and human being in return. For this reason, this study selected Core SCS-12 from the southwestern slope of SCS, to examine the reflection of the last deglaciation in the SCS.

1 Material and methods

Core SCS-12 was collected by the R/V Ocean Research I using a Kullenberg-type piston corer (7°42.0′N, 109°17.9′E, water depth 543 m, core length 120 cm). The sediment in the core is dark-gray silty clay. A total of 48 samples were taken with 2.5 cm interval and length.

All samples were processed using standard techniques. The coarser fraction ($>154\ \mu m$) was split into representative aliquots, from which planktonic and benthic foraminifera and pteropoda were picked, identified and counted. Then, the abundance of every kind of microfossil and relative abundance of each taxon were calculated. Furthermore, the sea surface temperature (SST) was calculated using planktonic foraminiferal transfer function; and the sea surface salinity (SSS) and phosphate-P content were estimated using the method of weighted mean based on the planktonic foraminiferal optimum values of environmental variables[6]. In addition, the changes in surface productivity are quantitatively estimated according to benthic foraminiferal abundance[7].

4—5 specimens of benthic foraminifera *Cibicidoides wuellerstorfi* (Schwager) (300—500 μm) were picked from each sample, and their stable isotopes were measured by a Finnigan/MAT Delta mass spectrometer at the Institute of Marine Geology, Qingdao. The precision is 0.07 ‰ for oxygen and 0.05 ‰ for carbon, respectively. Planktonic foraminifera *Neogloboquadrina dutertrei* ($>154\ \mu m$) were picked from two samples at depths of 30.0—32.5 cm and 112.5—117.5 cm for AMS ^{14}C dating at the Rafter Radiocarbon Laboratory, New Zealand. Further, more samples for dating are being prepared. In addition, 1 g dry sediment was taken from each sample and measured for $CaCO_3$ content using the conventional method of acid-base titration.

2 Results and discussion

2.1 Stratigraphy

The AMS ^{14}C ages at depths of 30.0—32.5 cm and 112.5—117.5 cm in Core SCS-12 are (7.70 ± 110) ka B.P. and (12.64 ± 120) ka B.P. respectively (the reservoir effect of 400 years between sea and atmosphere has been corrected). Based on the $\delta^{18}O$ curve of *C. wuellerstorfi*, the oxygen isotopic stage 1/2 boundary is set at depth of 78.75 cm and its age is determined to be 12.05 ka B.P. according to the $\delta^{18}O$ time scale of Martinson et al.[8] (fig. 1). Because the greatest amplitude of variation in $\delta^{18}O$ is 1.76 ‰ in the core, which has reached the glacial-interglacial $\delta^{18}O$ range of benthic foraminifera in the open ocean, the bottom of the core is thus inferred to correspond to the early last deglaciation with the age of about 13 ka B.P.

The abundance of planktonic foraminifera *Pulleniatina obliquiloculata* remarkably decreased at depths of 12.5—20.0 cm in the core (nearly zero). This minimum zone has been recognized as a common stratigraphic signature in the SCS and Okinawa Trough with the late Holocene age of about 3—5 ka B.P.[9], which is consistent with the interpolated age (table 1). Therefore, it seems reasonable to assume no obvious absence of sediment on the top of the core.

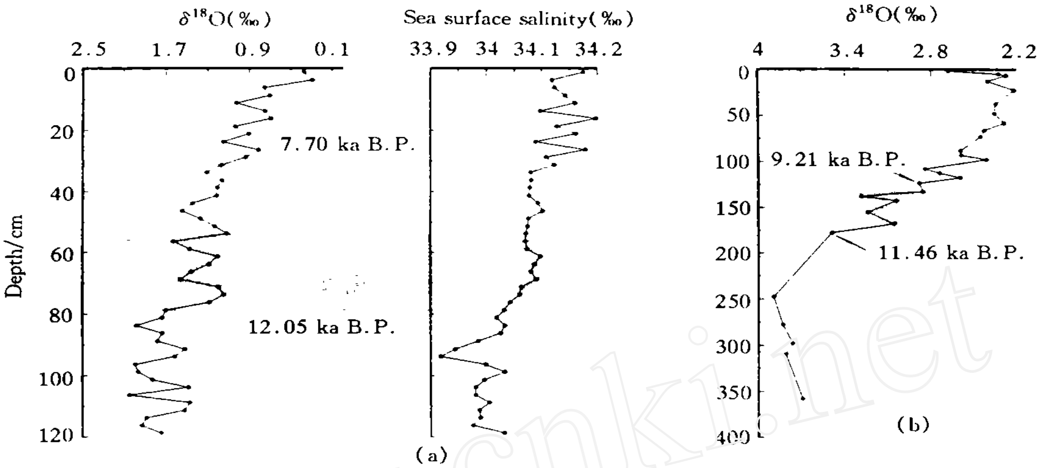

Fig. 1. Curves of $\delta^{18}O$ and sea surface salinity from Core SCS-12 and their comparison with that of $\delta^{18}O$ from Core V35-05[4] in the southern South China Sea. The shadow indicates the period of Younger Dryas.

Table 1 Average sedimentation rates of different parts in Core SCS-12

Part	Average sedimentation rate/cm·ka^{-1}	$CaCO_3$ (%)	$CaCO_3$ sedimentation rate/cm·ka^{-1}	Non-$CaCO_3$ sedimentation rate/cm·ka^{-1}
After termination I_B	4.1	15.2	0.6	3.5
Between terminations I_A and I_B	10.9	8.2	0.9	10.0
Before termination I_A	61.4	5.4	3.3	58.1

2.2 $\delta^{18}O$ and stepwise sea level changes

During the last deglaciation, the benthic foraminiferal $\delta^{18}O$ of Core SCS-12 varied stepwise (fig. 1), and rapidly decreased around 12.05 and 7.70 ka B.P. with the amplitudes of 0.84 ‰ and 0.50 ‰, respectively, which are equivalent to 1/2 and 1/3 of those of glacial-postglacial difference. However, between the two periods is an interval where $\delta^{18}O$ values remain stable, even with returns. Actually, it is doubtless that the stepwise curves of $\delta^{18}O$ in marine sediment during the last deglaciation have been reported from many parts of the ocean in the world[10,11]. Based on the $\delta^{18}O$ curves, Duplessy et al. proposed that the last deglaciation has experienced three periods: termination I_A and termination I_B of rapid ice sheet melting, which are separated by a pause even with an increase in ice volume[10]. The opinions on the age of the later termination (I_B) are unanimous (10—7 ka B.P.), while those on the age of the earlier termination (I_A) are quite different. However, in recent studies, the results of stacked $\delta^{18}O$ curve in different areas indicate that the age of termination I_A is around 14—12 ka B.P.[11]. Therefore, we suggest that in Core SCS-12 the periods of rapid change in $\delta^{18}O$ around 12.05 and 7.70 ka B.P. correspond to termination I_A and termination I_B, respectively.

During the late Quaternary, the changes in $\delta^{18}O$ of epifaunal benthic foraminifera *C. wuellerstorfi* mainly reflect the decrease and increase of ice volume in polar regime and the rise and fall of sea level. Therefore, the stepwise pattern of $\delta^{18}O$ curve of this species in Core SCS-12 during the last deglaciation indicates that the sea level might have stepwise varied: rapidly rose around 12.05 and 7.70 ka B.P. with an interval when the sea level slowly rose or even was at a standstill. This is also supported by the records of sea level rise in Barbados coral area, where the sea level rapidly rose 24 and 28 m at nearly 12 and 9 ka B. P. respectively[12].

Previous studies show that the sea level of the SCS dropped about 100—120 m during the last glacial maximum[5]. This paper adopts the middle value, i.e. the sea level was 110 m lower than the present at the beginning of the last deglaciation. According to the changes in δ^{18}O from the heaviest values (2.05 ‰) before termination I_A to 0.37 ‰ of core-top sample (0—2.5 cm in depth), the rapid sea level rise in the SCS around 12.05 and 7.70 ka B. P. are estimated to be about 55 and 33 m, respectively. If the average values of δ^{18}O before termination I_A, between terminations I_A and I_B, and after termination I_B (1.77 ‰, 1.29 ‰ and 0.77 ‰ respectively) are applied, it can be inferred that the sea level during the period between terminations I_A and I_B was roughly around -50 m; that is, the SCS displayed three different paleogeographic scenarios since the last deglaciation: the situations before termination I_A (-110 m), between terminations I_A and I_B (-50 m) and after termination I_B (about 0 m) (figure 2).

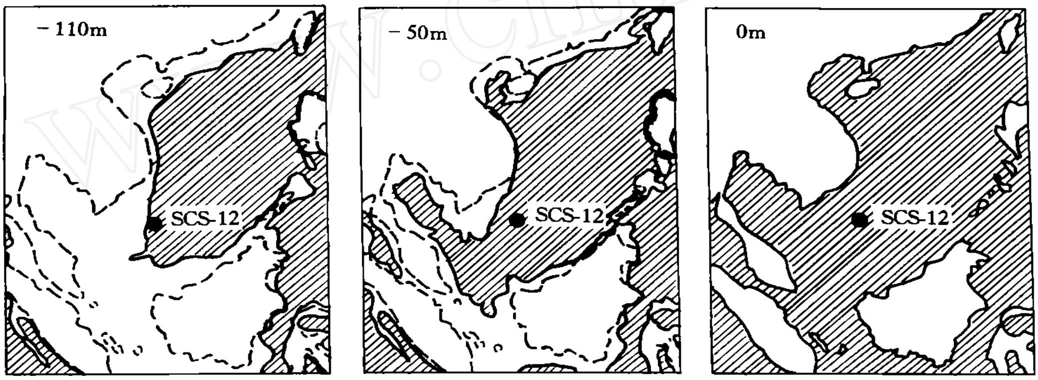

Fig. 2. Paleogeographic scenarios of the SCS during the three steps of sea level change since the last deglaciation.

Before termination I_A, the sea level of the SCS was located at -110 m, the broad shelf in the southern part emerged, hence the site of Core SCS-12 was very close to the shoreline (fig. 2). At that moment, a vast amount of terrigenous materials could have been brought directly to the upper slope, not only increasing the sedimentation rate of Core SCS-12 (as high as 61.4 cm/ka), but also diluting the $CaCO_3$ content to the average 5.4 % (table 1). Through the rapid sea level rise of termination I_A, the sea level was located at about -50 m; the distance between the core and the shoreline increased; hence most of terrigenous materials were unloaded on the shelf. The sedimentation rate abruptly decreased by about 5/6, averaging 10.9 cm/ka. After termination I_B, the core was much closer to the estuarine than before, the sedimentation rate declined to the average 4.1 cm/ka, only about 1/15 of that before termination I_A (table 1).

Based on the planktonic foraminiferal optimum values of salinity[6], the changes of the SSS at Core SCS-12 could be estimated by the method of weighted mean. It has been found that the SSS also stepwise increased (fig. 1), further confirming that the distance between the core and the estuarine increased with the stepwise sea level rise, consequently the influence of fresh water on the core more and more declined.

2.3 Significant changes in sea surface temperature and paleo-productivity of termination I_A

The faunal assemblage was dominated by the warm species, such as *N. dutertrei*, *Neogloboquadrina pachyderma*, *Globorotalia inflata*, before termination I_A in Core SCS-12. On the contrary, the abundance of tropic-species planktonic foraminifera *Globigerinoides ruber*, *Globorotalia menardii*, *P. obliquiloculata* and others remarkably decreased (fig. 3). The winter and summer SSTs were calculated using planktonic foraminiferal transfer function FP-12E[2]: (i) Before termination I_A, the winter and summer SSTs were 21.1 and 27.7 °C respectively, 4.7 and 0.9 °C lower than today (25.8 and 28.6 °C) respectively. The difference between the winter and summer SSTs was as high as 6.6 °C, indicating that the seasonality was much stronger than that of today (2.8 °C). (ii) The conspicuous increase in winter and summer SSTs during the last deglaciation occurred at the end of termination I_A around 12.05 ka B. P. Their amplitudes were 4.0 and 1.4 °C respectively (fig. 3), much greater than those at similar latitudes in the western Pacific[2]. It is thus clear that the southern SCS also experienced the relatively remarkable glacial-postglacial changes in the SSTs.

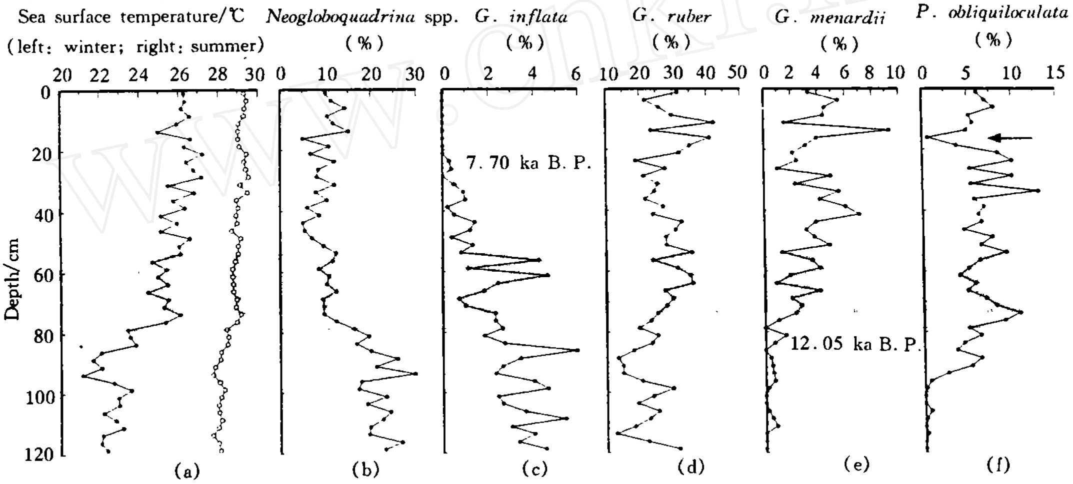

Fig. 3. Variations in the sea surface temperature and relative abundance of planktonic foraminiferal taxa in Core SCS-12. The shadow area indicates the period of Younger Dryas. The arrow shows the minimum zone of *P. obliquiloculata* abundance during the late Holocene at about 3—5 ka B. P.

The surface primary productivity of Core SCS-12 was quantitatively estimated according to the formula of Herguera and Berger[7]. Before termination I_A, the average surface primary productivity PP was as high as 175.4 gC/m^2·a^{-1}, which was 2—4 times more than that after termination I_A (fig. 4). Meanwhile, the sea surface phosphate-P content estimated by the method of weighted mean[6], obviously decreased after termination I_A (fig. 4). The percentage abundance of benthic foraminifera *Uvigerina peregrina*, *Melonis barleeanus*, *Globobulimina* spp., *Chilostomella oolina*, and others indicative of high organic carbon in sediments and low dissolved oxygen content in bottom water also significantly decreased after termination I_A (fig. 4), indicating the abrupt decrease in surface paleo-productivity at termination I_A. It is very likely that after termination I_A, a lot of terrigenous nutrient was not transported directly to the upper slope again, and hence the surface phosphate-P content and paleo-productivity decreased.

In fact, during termination I_A around 12.05 ka B. P., the noticeable increase in the SSTs and decrease in surface paleo-productivity have also been found in other parts of the SCS basin as well as the Sulu Sea[2,3,13]. This should not be an accidental and individual phenomenon.

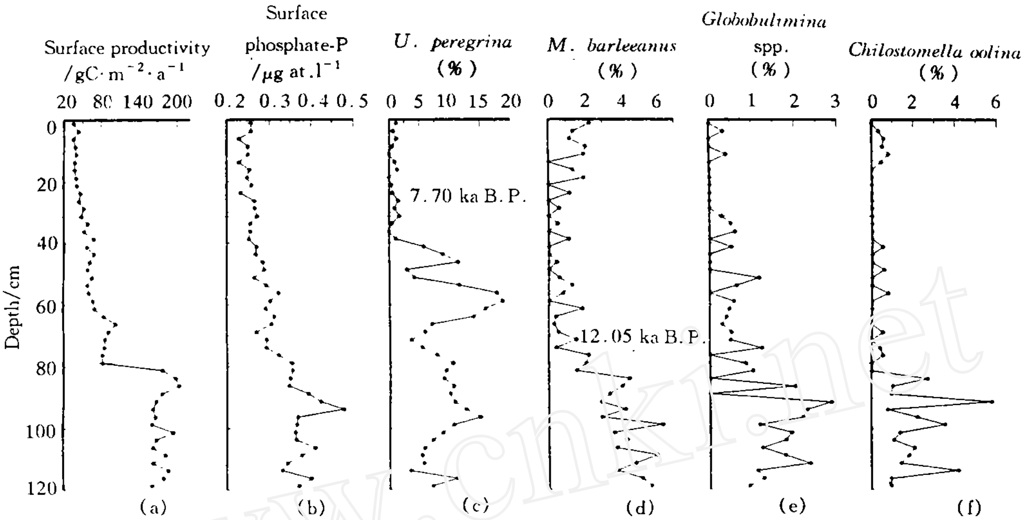

Fig. 4 Planktonic and benthic foraminiferal index showing the changes of surface paleo-productivity at Core SCS-12.

2.4 $CaCO_3$ preservation spike of termination I_B

Broecker et al. pointed out that the air bubbles from the Antarctica Byrd ice core recorded a decrease in CO_2 content during the early Holocene at about 10.0—7.0 ka B. P., in correspondence with the peak abundance of pteropoda or $CaCO_3$ content in deep-sea sediments of the Atlantic (about 8.5 ka B. P.). It demonstrates that due to the early Holocene forest and soil regrowth, the atmospheric CO_2 content decreased, leading to an increase in the CO_3^{2-} ion concentration of deep water and a decline of the carbonate lysocline, hence the carbonate preservation spike. This is a return event superimposed on the oceanic carbonate lysocline rose since the end of the last glacial stage[14].

During termination I_B at about 8.8—6.5 ka B. P. in Core SCS-12, there is a distinct zone of high abundance of pteropoda. The ratio between pteropoda and planktonic foraminifera also has peak values during this period (fig. 5). Previous studies have shown that the preservation spike of pteropoda extended into the Holocene Hypsithermal at about 6—7 ka B. P. in the southern SCS and Sulu Sea[13,15]. This indicates that the carbonate dissolution remarkably decreased at this moment because aragonite pteropoda are more susceptible to dissolution than calcite planktonic foraminifera.

Though the sedimentation rate of $CaCO_3$ decreased from 3.3 cm/ka before termination I_A to 0.6 cm/ka after termination I_B, the $CaCO_3$ content continuously increased due to the decrease in the input of terrigenous material to this region. However, the remarkable increase in the $CaCO_3$ content during termination I_B at about 7.70 ka B. P. (>12 %, table 1, fig. 5) is hardly completely explained by the changes in the sedimentation rate of non-$CaCO_3$, and it should also be related to the better preservation of $CaCO_3$ at that moment. This characteristic of the change in $CaCO_3$ content has also been reflected in the curves of coarse fraction (>63 μm) % and planktonic foraminiferal abundance (fig. 5). Therefore, during termination I_B around 7.70 ka B. P. in Core SCS-12, the noticeable increase in the abundance of pteropoda and $CaCO_3$ content indicates that the early Holocene $CaCO_3$ preservation spike event[14] also occurred in the SCS, suggesting that it is a possible global signature.

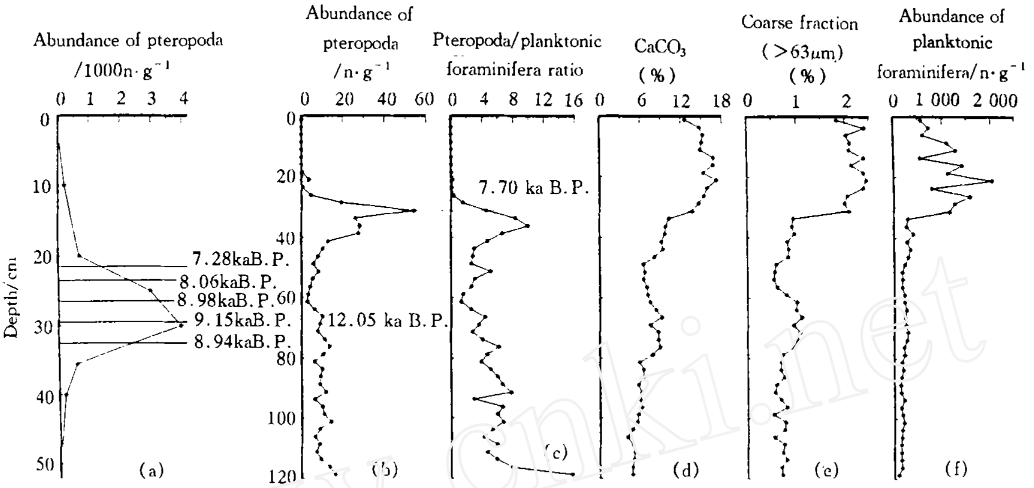

Fig. 5 The abundance of pteropoda in Core V30-60 of the Atlantic[14] and its comparison with the abundance of pteropoda, ratio between pteropoda and planktonic foraminifera, $CaCO_3$ content, coarse fraction and abundance of planktonic foraminifera in Core SCS-12 of the SCS.

2.5 Younger Dryas Event ?

Younger Dryas Event is a short-term climatic cooling about 11—10 ka B. P. It was found only in the Atlantic and its adjacent European and American continents before[16]. In the last few years, however, Younger Dryas Event has also been reported from the Sea of Japan, East China Sea, SCS and its adjacent Sulu Sea[3,16], showing that this event is a global one.

As shown from fig. 1, in Core SCS-12 at depths of 52.5—75.0 cm (11.6—9.8 ka B. P.), the benthic foraminiferal $\delta^{18}O$ increased with the amplitude of about 0.58 ‰, which is equivalent to about 1/3 and 2/3 of those during the deglaciation and termination I_A, respectively. Particularly, the fluctuation of $\delta^{18}O$ changed by three phases: two increases with a short decrease between them (fig. 1). This special feature is not only evidenced by the $\delta^{18}O$ curves of benthic foraminifera *Cibicidoides* in Core V35-05 (7°11′N, 112°05′E) of the southern SCS[4] (fig. 1), but can be correlated to the records of peat from the desert/loess transition zone in Chinese inland, supporting that the East Asian climate had experienced the changes from dry and cold, to warm and cool, and then to dry and cold during the Younger Dryas period[17]. During this period, the abundance of warm-species *Neogloboquadrina* spp. and *G. inflata* and others abruptly increased. Correspondingly, the winter SSTs decreased by about 1.6 ℃ (fig. 3), equivalent to 26 % of the amplitude during the deglaciation, and the seasonality also increased to 4.3 ℃ from 3.1 ℃ before the cooling. In fact, there were similar changes in Core V36-06-3 of the northern SCS during the Younger Dryas period, but with greater amplitude than that in the southern part.

Though precise datings are to be done, we believe that the short-term climatic return revealed by $\delta^{18}O$ and foraminifera in Core SCS-12 at depths of 52.5—75.0 cm (about 11.6—9.8 ka B. P.) should be the reflection of Younger Dryas Event SCS. The $\delta^{18}O$ shift during the Younger Dryas period in the western Pacific was found only in planktonic foraminiferal before, not in benthic foraminiferal curves. However, it was also recognized from the $\delta^{18}O$ curves of *Cibicidoides* in Cores SCS-12 and V35-05[4]. It seems that this phenomenon needs further study.

3 Conclusions

The stepwise paleoceanographic changes in the southern SCS since the last deglaciation are not only influenced by the global changes, but also controlled by the geographic and paleoceanographic changes in the SCS and western Pacific. The δ^{18}O in Core SCS-12 and the sea level in the southern SCS stepwise changed during the last deglaciation. Around 12.05 and 7.70 ka B.P. are two rapid change periods corresponding to termination I_A and termination I_B respectively, in between is a slow change period. It is inferred that compared with that of modern, the sea level stood at - 110 m before termination I_A, and roughly the same after termination I_B, but about - 50 m between them, thus leading to a series of changes in environmental index. For example, since the last deglaciation the sedimentation rate stepwise decreased, while the SSS stepwise increased. Since termination I_A about 12.05 ka B.P., the winter SSTs obviously increased, while surface paleo-productivity decreased. But around termination I_B about 7.70 ka B.P., the abundance of pteropoda and $CaCO_3$ content remarkably increased, and then the early Holocene $CaCO_3$ preservation spike occurred. In addition, the benthic foraminiferal δ^{18}O, SSTs and so on in Core SCS-12 also have recorded the Younger Dryas Event during about 11.6—9.8 ka B.P.

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