Article
Chinese Science Bulletin

Oceanology
August 2011 Vol.56 No.24: 2628–2634
doi: 10.1007/s11434-011-4590-0

Response of the northwestern Pacific upper water δ^{13}C to the last deglacial ventilation of the deep Southern Ocean

CHEN ShuangXi[1,3], LI TieGang[1*], TANG Zheng[1,2,3], QIU XiaoHua[1,3], XIONG ZhiFang[1], NAN QingYun[1], XU ZhaoKai[1] & CHANG FengMing[1]

[1] *Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China;*
[2] *Key Laboratory of Marine Hydrocarbon Resources and Environmental Geology, Qingdao Institute of Marine Geology, Ministry of Land and Resources of China, Qingdao 266071, China;*
[3] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

Received March 3, 2011; accepted May 13, 2011

The deglacial δ^{13}C minimum events that originated from the ventilation of the deep Southern Ocean around Antarctica, have been recorded in a range of marine sediments from the southern to tropical oceans in late Pleistocene. However, the broad δ^{13}C minimum event was also reported as far as to the northern middle latitudes, in northwestern Pacific marginal sea areas, during the last deglaciation. In the northwestern Pacific, forcing from the northern high latitudes is strongly expressed, while the records of influence from the southern high latitudes are few. The Kuroshio Source Region (KSR) forms a boundary between the northwestern Pacific and the southern, tropical Pacific. So, high-resolution planktonic foraminiferal records in core MD06-3054 from the KSR are well positioned to identify signals from the southern hemisphere in the northwestern Pacific. Planktonic foraminiferal tests from the upper 1030 cm of the core were subject to AMS^{14}C, carbon and oxygen isotopic measurements. A negative excursion was found to occur from about 20.0–6.0 ka BP in δ^{13}C records of both surface (*Globigerinoides ruber*) and subsurface (*Pulleniatina obliquiloculata*) dwellers, but the overall trends of the two curves have reversed since 26.5 ka BP. Moreover, the δ^{13}C record of *G. ruber* (the surface dweller) shows a robust link to the record of atmospheric CO$_2$, and its changes precede the records of *P. obliquiloculata* (the subsurface dweller). According to the hydrologic conditions, the broad δ^{13}C minimum event recorded in the KSR is also a response to the increasing ventilation of the deep Southern Ocean around Antarctica during the last deglaciation. The inconsistency between the records of the surface and subsurface dwellers was possibly caused by the ways that the low δ^{13}C signal was transmitted. Subsurface water primarily received the low δ^{13}C signal from the Antarctic Intermediate Water (AAIW), whereas the surface water was probably mainly impacted by atmospheric CO$_2$ in the KSR. The records from the KSR confirm the deduction that the broad δ^{13}C minimum event in the Okinawa Trough was due to the impact of tropical Pacific surface water during the last deglaciation, and suggest that signals from the southern high latitudes also can be delivered to the northern middle latitudes.

planktonic foraminiferal δ^{13}C, ventilation of the deep Southern Ocean, northwestern Pacific, last deglaciation, δ^{13}C minimum event

Citation: Chen S X, Li T G, Tang Z, et al. Response of the northwestern Pacific upper water δ^{13}C to the last deglacial ventilation of the deep Southern Ocean. Chinese Sci Bull, 2011, 56: 2628–2634, doi: 10.1007/s11434-011-4590-0

In recent research, the ventilation of the deep Southern Ocean during recent glacial cycles is considered to link closely with the changes in atmospheric CO$_2$ [1–5]. The release of the CO$_2$ accumulated in the deep sea would change the concentrations and carbon isotopes of atmospheric CO$_2$ with an outcrop of deep ocean water around Antarctica during deglaciations [1–3,5,6]. Records of opal flux from Anderson et al. [1], evidence of planktonic and benthic foraminiferal ^{14}C from Skinner et al. [2] both document that the increasing ventilation of the deep Southern

---

*Corresponding author (email: tgli@qdio.ac.cn)

Ocean was coincident with the rising of atmospheric CO_2 recorded in ice cores during the last deglaciation. During this time, the isotopic changes of atmospheric CO_2 correspond with the new outgassing, which was especially depleted in δ^{13}C and Δ^{14}C [2,6–9]. On the other hand, with supersaturated deep water driven to the sea surface, the low δ^{13}C signal was subsequently transmitted northward via Antarctic Intermediate Water (AAIW)/sub-Antarctic Mode Water (SAMW) [1,6,10], and caused the δ^{13}C minimum event recorded in marine sediments from the southern to tropical oceans [6,11,12]. However this event was also reported in northwestern Pacific marginal seas [13,14], as far away as the Okinawa Trough [15]. Though impacts from the southern high latitudes are reported widely in the tropical Pacific [6,10,16–19], there are few records of causal effects from southern hemisphere in the northwestern Pacific. In contrast, forcing from the northern high latitudes is strongly expressed in this area, especially in the Okinawa Trough [20–22].

The Kuroshio Source Region (KSR) forms a boundary between the northwestern Pacific and the southern, tropical Pacific region, so core MD06-3054 in this area is well positioned to identify influences from the Southern Hemisphere (Figure 1(a)). Here, the response of the northwestern Pacific upper water δ^{13}C to the last deglacial ventilation of the deep Southern Ocean is examined using the carbon isotope composition of planktonic foraminifera tests, which is often used to reconstruct the history of water masses [6,10,23].

1 Oceanographic setting

In the northwestern Pacific, the westward-flowing Northern Equatorial Current (NEC) bifurcates into the northward-flowing Kuroshio Current (KC) and the southward-flowing Mindanao Current (MC) at an average latitudinal position of about 15°N, after approaching the Philippine coast [24–28] (Figure 1(a)). The KC flows along the northern Philippine coast and out of the KSR to the east of Taiwan, then continues northward into the Okinawa Trough, carrying warm and saline water from the tropical Pacific to the northern middle latitudes, and having a significant impact on the environment and climate of the northwestern Pacific region [20,29]. Below the surface, the southern source water — the AAIW — can intrude into the KSR via the New Guinea Coastal Undercurrent and the Mindanao Undercurrent (MUC) [24,27]. Qu and Lindstrom [25] found that the AAIW is traced only to about 15°N based on both salinity and oxygen concentration. The high-oxygen concentration of the AAIW is shown to have been substantially decreased, falling below 2.0 mL L^{-1}, at about 15°N in the $27.2\sigma_\theta$ surface via MUC from historical data and six hydrographic section in the western Pacific Ocean (12°N, 14°N, 16°N, 18°N, 20°N, 22°N) [24] (Figure 1(b)). So it can not be the source of the relatively high oxygen (2.0 mL L^{-1}) water existed in the Okinawa Trough [24]. Moreover, the subsurface flow near the coast is dominated by the southward-flowing Luzon Undercurrent (LUC) with relatively low (<1.9 mL L^{-1}) oxygen level at 16°–18°N, which also indicates that there is no northward flow of AAIW over 15°N [25] (Figure 1(b)). The AAIW originates from the surface water in the sub-Antarctic band [19,25], along with another water mass — the SAMW, which have important impact on the subsurface water in the upwelling region of the eastern equatorial Pacific (EEP) [10,19,30]. The two water masses provide crucial channels that enable the southern high latitudes to influence the tropics [1,6,10,19,30].

2 Materials and methods

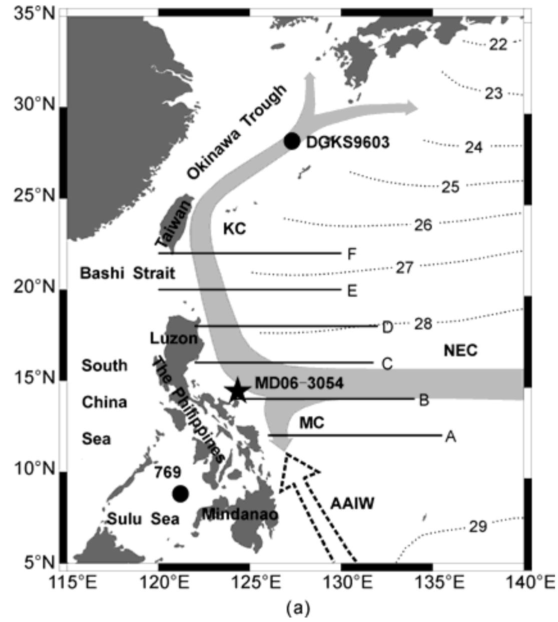
The Calypso core MD06-3054 (14°30.2816′N, 124°19.2400′E; water depth: 2021 m), located at the westernmost terminus of the NEC in the Philippine Sea, northwestern Pacific (Figure 1(a)), was obtained during the joint Chinese-French Marco Polo 2 cruise in Western Pacific in 2006. Samples were taken at 4 cm intervals from the upper 1030 cm of the core, and each sample was treated with the standard techniques [31]. 15–20 tests of *Globigerinoides ruber* (size fraction from 250 to 300 μm) and 5–8 tests of *Pulleniatina obliquiloculata* (size fraction from 300 to 400 μm) were hand-picked carefully for stable isotope analysis with the Finnigan MAT 253 at the State Key Laboratory of Marine Geology, Tongji University. Precision was checked against international standard NBS19. Standard deviation was ±0.07‰ for δ^{18}O and ±0.04‰ for δ^{13}C in 2008. Conversion to the international Pee Dee Belemnite (PDB) scale was based on the NBS19 standard.

The tests of mixed species *Globigerinoides sacculifer* and *G. ruber* (size fraction from 250 to 350 μm) were hand-picked with caution and subjected to AMS ^{14}C measuring in the National Ocean Sciences Accelerator Mass Spectrometry Facility at the Woods Hole Oceanographic Institute, USA. The raw AMS ^{14}C ages were converted to calendar ages using the CALIB 6.0 program (http://calib.qub.ac.uk/calib/) with the dataset Marine 09 [32]. A reservoir correction has been considered for the ^{14}C difference between atmospheric and surface waters [33].

3 Age model

The age model is based on 8 AMS^{14}C and the δ^{18}O records of *G. ruber* and *P. obliquiloculata* (Table 1, Figure 2(c), (d)). The age model assumes that the upper 1030 cm of core MD06-3054 contain a continuous record since 26.5 ka BP, with an average temporal resolution of 245 a before 11.2 ka BP and 58 a afterwards at a 4 cm sampling interval.

The oxygen isotope records of planktonic foraminifera *G. ruber* and *P. obliquiloculata* show a classic glacial/inter-



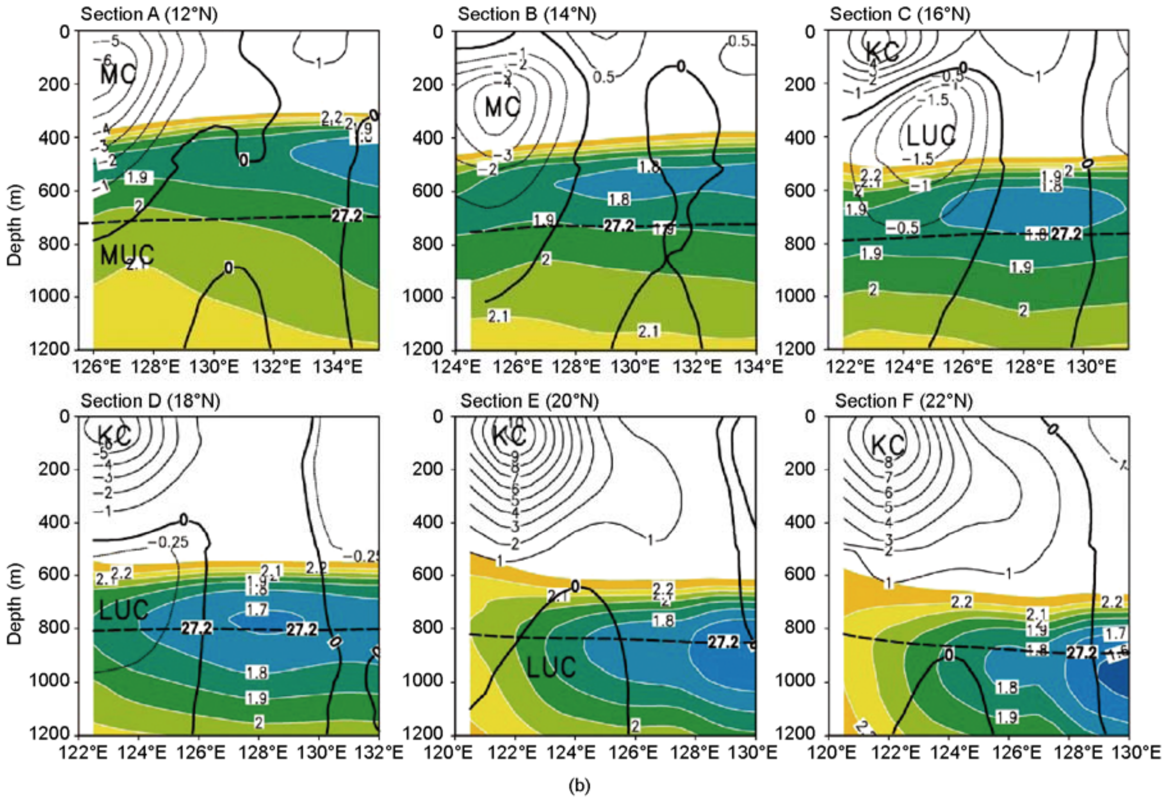


Figure 1 (a) Location of core MD06-3054 in the KSR, and the sites and the hydrological settings associated in the northwestern Pacific. The connected ocean currents (AAIW, NEC, KC, and MC) are shown with solid and dashed arrows, and the dashed contours are the annual average sea surface temperature (°C) at present (Data from WOA 05). The solid lies (ABCDEF) show the six geographic locations of vertical sections in Figure 1(b); (b) geostrophic velocity (cm s^{-1}) against depth (m) superimposed on oxygen concentration (mL L^{-1}) at the six vertical sections: A (12°N), B (14°N), C (16°N), D (18°N), E (20°N), and F (22°N) modified from Qu and Lindstrom [24]. Positive values of geostrophic velocity are northward, and negative values are southward. The heavy dashed lines indicate the 27.2 σ_θ isopycnal surface [24].

Table 1 AMS^{14}C age points measured in the upper 1030 cm from core MD06-3054

Sample No.	Depth (cm)	Material	AMS^{14}C (a)	Cal age (a BP)	Age errors (a)	
					−σ	+σ
OS-72806	19	*G. ruber* + *G. sacculifer*	930±30	546	65	83
OS-72709	327		3020±30	2804	87	114
OS-72962	447		4980±50	5353	157	186
OS-72965	563		7080±35	7573	99	91
OS-72712	675		9320±45	10181	181	159
OS-72966	779		10250±40	11240	92	130
OS-72808	827		11900±45	13342	113	121
OS-72803	1019		22000±85	25901	468	359

glacial pattern since 26.5 ka BP in MD06-3054. Note that the values are more positive during the last glacial period than during the Holocene (Figure 2(c), (d)). The values decreased by over 2‰ in the last deglaciation and the decreasing trend was obviously relaxed during the mid-late Holocene.

4 Results and discussion

Both δ^{13}C curves of the planktonic foraminifera *G. ruber* and *P. obliquiloculata* fluctuate greatly, even within a time period several hundred years. The δ^{13}C records change from 0.020‰ to 1.858‰ and from –0.021‰ to 1.677‰ for *G. ruber* and *P. obliquiloculata*, respectively (Figure 2(a), (b)). The δ^{13}C of foraminiferal tests is mainly a representation of the isotope compositions of the sea water in which they lived, thereby providing a readily accepted method to reconstruct the evolution of sea water masses in paleoceanographic research [6,10,23]. In this work, the test size fraction was restricted to minimize its effect [34] on isotope analysis. The serious fluctuations of the δ^{13}C records may reflect the influence of other factors, such as sea surface productivity, nutrient supply and terrestrial inputs [14,15,23, 34]. However, there are two obvious features in both planktonic foraminiferal δ^{13}C records for core MD06-3054 since 26.5 ka BP. One is the negative excursion from about 20.0–6.0 ka BP in both records, and the other is that the trends of the two curves show an overall reversed pattern since the last glacial: the δ^{13}C records of *G. ruber* show an increasing trend, and the values are more positive during the late Holocene than the last glacial period, whereas for *P. obliquiloculata*, the δ^{13}C records show a decreasing trend, and the values are more positive during the last glacial period (Figure 2(a), (b)).

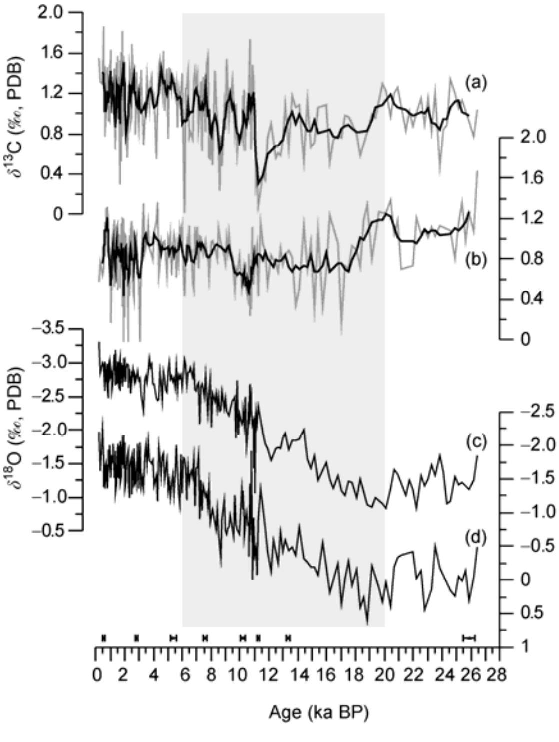


Figure 2 The δ^{13}C and δ^{18}O records of planktonic foraminifera *G. ruber* and *P. obliquiloculata* from core MD06-3054 since 26.5 ka BP. Black solid lines in (a) and (b) indicate five-point running average records. The shaded area indicates the negative excursion that occurred from about 20.0–6.0 ka BP. The AMS^{14}C age points are shown at the bottom with error bars (2σ).

The negative excursion that occurred from about 20.0–6.0 ka BP in both δ^{13}C records from core MD06-3054 agrees well with the broad δ^{13}C minimum event recorded during the last deglacial period in southern high latitudes [35], the Indian Ocean [36], the Atlantic Ocean [37], the EEP [6,36], and western Pacific marginal sea areas [13–15] (Figure 3). The cause of the deglacial δ^{13}C minimum events was proposed to be due to upwelling of the deep Southern Ocean around Antarctica by Oppo and Fairbanks [11] for the tropical Atlantic and by Spero and Lea [6] for the EEP. During the last deglaciation, increased ventilation of the deep Southern Ocean has recently been documented by opal flux and foraminiferal ^{14}C records [1,2]. On the one hand, with supersaturated deep water driven to the sea surface, the concentration of atmosphere CO_2 increased and its carbon isotopes changed in response to the outgassing of low δ^{13}C and Δ^{14}C CO_2 resolved in the deep ocean water [2,6–9,38]; on the other hand, the low δ^{13}C signal was advected into the source region of the AAIW/SAMW and subsequently transmitted northward via AAIW/SAMW [1,6,10]. The negative excursion that occurred from about 20.0–6.0 ka BP, as recorded in the planktonic foraminifera from core MD06-3054, shows that the last deglacial low δ^{13}C signal from the ventilation of the deep Southern Ocean in the southern high latitudes also transmitted to the KSR.

In modern physical oceanographic research, the AAIW can intrude to the KSR [25,27], which may provide a means of transporting the low δ^{13}C signal into this area during the last deglaciation. The δ^{13}C record of the subsurface dweller *P. obliquiloculata* since 26.5 ka BP also infers the impact of the AAIW on the KSR. The decreasing trend reverses the record of the surface dweller *G. ruber*, with values that are more positive during the last glacial period than during the late Holocene, which is consistent with the record from the upwelling region of the EEP [36]. Loubere and Bennett [10] have traced the impact of SAMW on the tropical ocean from southern high latitudes using planktonic foraminiferal δ^{13}C records in the southeastern Pacific, and they found that the planktonic foraminiferal δ^{13}C records from subsurface water in the upwelling region of the EEP and the subtropical frontal region, shared a similar decreasing trend with the surface water in the sub-Antarctic band — the source region of the SAMW, with the feature that the values were more positive during the last glacial period than during the late Holocene (Figure 3(c)). The AAIW and SAMW both come from the surface water in the sub-Antarctic band and can deliver signals from southern high latitudes northward [1,6,

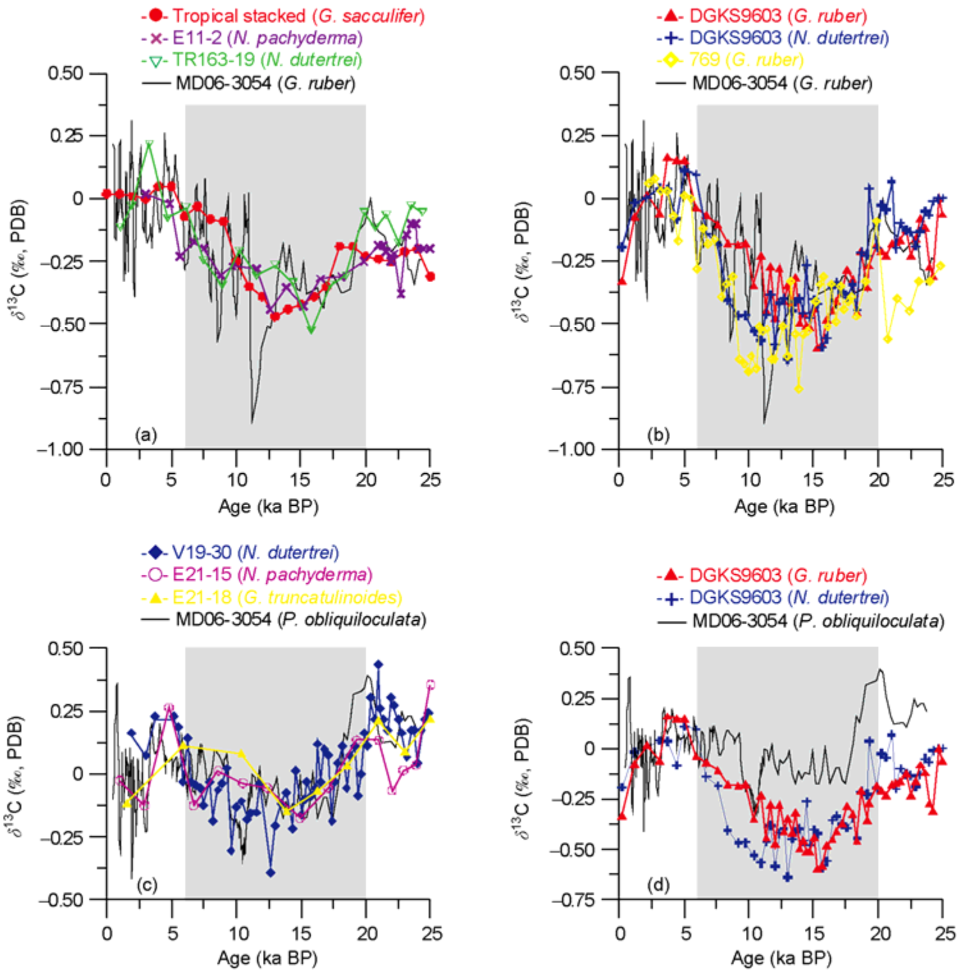


Figure 3 The δ^{13}C of *G. ruber* and *P. obliquiloculata* (black solid lines, five-point average) from core MD06-3054 since the last glacial in comparison with other records. The δ^{13}C of *G. ruber* compared with (a) records from stratified ocean settings [6,35,37] and (b) records from core DGKS9603 [15] and site 769 [14]. The δ^{13}C of *P. obliquiloculata* and compared with (c) records from the SAMW [10,36] and (d) records from core DGKS9603 [15]. Values have been normalized to a late Holocene averages. The shaded area indicates the δ^{13}C minimum event.

19], so they should share the same history since the last glacial. The consistent pattern of subsurface dweller δ^{13}C records from the KSR and the upwelling region of the EEP since the last glacial supports the influence of the AAIW on the KSR.

Differing from the record of *P. obliquiloculata*, the δ^{13}C record of the surface dweller *G. ruber* shows an increasing trend since the last glacial, with values that are more positive during the late Holocene than during the last glacial period, which agrees with the records from stratified ocean settings [6,35,37] (Figure 3(a)). Spero and Lea [6] explored the cause of the deglacial δ^{13}C minimum events outside of the upwelling region in the EEP by examining the concentration and carbon isotopic records of atmospheric CO_2 in the Antarctic Taylor Dome ice core [8], and argued that the low δ^{13}C signal was also delivered northward by atmospheric CO_2 during the deglaciations. The record from a marginal area of western Pacific — the Sulu Sea — also supports this view. Decreased sea level would greatly restrict the influx of western Pacific surface water from the South China Sea to the Sulu Sea during deglaciations, so the obvious negative excursions in the planktonic foraminiferal δ^{13}C record of surface dweller from site 769 were considered to contribute to the increased atmospheric CO_2 from the upwelling of the Pacific intermediate water in the far western Pacific [14] (Figure 3(b)). According to recent research, the CO_2 was possibly released from the ventilation of the deep Southern Ocean around Antarctica [1,2,6]. The minima of the δ^{13}C average record of the surface dweller *G. ruber* in core MD06-3054 appear from about 13.0–11.0 ka BP (Figure 2(a)), agreeing with the rise in atmospheric CO_2 in Antarctic ice cores [8,38], and the increase in ventilation of the deep Southern Ocean [1]. The time agreement suggests a robust link between surface water δ^{13}C and the atmospheric CO_2 in the KSR. Moreover, the different paces of the records of *G. ruber* and *P. obliquiloculata* also suggest an impact of atmospheric CO_2 on the surface water. Variations of δ^{13}C records in the surface dweller obviously preceded the subsurface dweller since 26.5 ka BP in core MD06-3054. This precedence can be seen both at the beginning of the δ^{13}C minimum event (20–17 ka BP) and at the time of the δ^{13}C minima (13–9 ka BP) (Figure 2(a), (b)).

During the last deglaciation, the low δ^{13}C signal was also delivered to the middle latitudes by the northward-flowing KC. Li et al. [15] reported the last deglacial broad δ^{13}C minimum event recorded in core DGKS9603 (28.15°N, 127.27°E), located in the middle of the Okinawa Trough. The δ^{13}C records of both surface and subsurface dwellers show a consistent trend since the last glacial in core DGKS9603, which agree with the surface dweller record and reverse the subsurface dweller record in core MD06-3054 (Figure 3(b), (d)). The trends of the δ^{13}C records from the two cores confirm the deduction that the broad δ^{13}C minimum event in the Okinawa Trough was mainly due to the impact of tropical Pacific surface water directly during the last deglaciation [15]. The distribution of the last deglacial broad δ^{13}C minimum event in the Kuroshio drainage area indicates that signals from the southern high latitudes can be delivered to the northern middle latitudes.

5 Conclusion

The broad negative excursion that occurred from about 20.0–6.0 ka BP appears in both planktonic foraminiferal δ^{13}C records of *G. ruber* (a surface dweller) and *P. obliquiloculata* (a subsurface dweller) in core MD06-3054 from the KSR, in the northwestern Pacific. The negative excursion is consistent with the last deglacial broad δ^{13}C minimum event recorded in oceans globally. However, the overall trends of the δ^{13}C records are reversed since 26.5 ka BP: the δ^{13}C records of *G. ruber* show an increasing trend, and the values are more positive during the late Holocene than during the last glacial period, which is consistent with the records from stratified ocean settings; whereas the records of *P. obliquiloculata* show a decreasing trend, and the values are more positive during the last glacial period, agreeing with the observations of the SAMW. Moreover, the δ^{13}C record of the surface-dwelling *G. ruber* shows a robust link to the record of atmospheric CO_2, and its changes also preceded the records of subsurface-dwelling *P. obliquiloculata*. Based on the hydrologic conditions, the broad δ^{13}C minimum event recorded in the KSR is also in response to the ventilation of the deep Southern Ocean around Antarctica during the last deglaciation. Inconsistency between the records of the surface and the subsurface dwellers was possibly caused by the different ways that the low δ^{13}C signal was transmitted. The subsurface water primarily received the low δ^{13}C signal from the AAIW, while the surface water was most likely impacted primarily by atmospheric CO_2. The records from the KSR confirm the deduction that the broad δ^{13}C minimum event in the Okinawa Trough was due to the direct impact of tropical Pacific surface water during the last deglaciation, and suggest that signals from southern high latitudes also can be delivered to the northern middle latitudes.

We thank the onboard scientists as well as officers and crew of R/V Marion Dufresne of the French Polar Institute (IPEV) for their help in sampling. We are grateful to Prof. Jian Zhimin and Cheng Xingrong of Tongji University for their assistance in isotope analysis. Thanks are also expressed to Prof. Yu Xinke of the Institute of Oceanology, Chinese Academy of Sciences, and Prof. Paul Loubere of Northern Illinois University for their discussions and good advice. Dr. Chen Shuai of the Institute of Oceanology, Chinese Academy of Sciences reviewed an early version of this paper, and constructive comments from the two reviewers improved this manuscript. This work was supported by the National Basic Research Program of China (2007CB815903), the Pilot Project of the National Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-221) and the National Natural Science Foundation of China (41076030 and 40906038).

1 Anderson R F, Ali S, Bradtmiller L I, et al. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. Science, 2009, 323: 1443–1448
2 Skinner L C, Fallon S, Waelbroeck C, et al. Ventilation of the deep Southern Ocean and deglacial CO_2 rise. Science, 2010, 328: 1147–1151
3 Denton G H, Anderson R F, Toggweiler J R, et al. The last glacial termination. Science, 2010, 328: 1652–1656
4 Sigman D, Boyle E. Glacial/interglacial variations in atmospheric carbon dioxide. Nature, 2000, 407: 859–869
5 Sigman D M, Hain M P, Haug G H. The polar ocean and glacial cycles in atmospheric CO_2 concentration. Nature, 2010, 466: 47–55
6 Spero H J, Lea D W. The cause of carbon isotope minimum events on glacial terminations. Science, 2002, 296: 522–525
7 Köhler P, Fischer H, Munhoven G, et al. Quantitative interpretation of atmospheric carbon records over the last glacial termination. Glob Biogeochem Cy, 2005, 19: GB4020, doi:10.1029/2004GB002345.
8 Smith H J, Fischer H, Wahlen M, et al. Dual modes of the carbon cycle since the Last Glacial Maximum. Nature, 1999, 400: 248–250
9 Hughen K, Lehman S, Southon J, et al. ^{14}C activity and global carbon cycle changes over the past 50000 years. Science, 2004, 303: 202–207
10 Loubere P, Bennett S. Southern Ocean biogeochemical impact on the tropical ocean: Stable isotope records from the Pacific for the past 25,000 years. Glob Planet Change, 2008, 63: 333–340
11 Oppo D W, Fairbanks R G. Carbon isotope composition of tropical surface water during the past 22000 years. Paleoceanography, 1989, 4: 333–351
12 Lynch-Stieglitz J, Fairbanks R G, Charles C D. Glacial-interglacial history of Antarctic Intermediate Water: Relative strengths of Antarctic versus Indian Ocean sources. Paleoceanography, 1994, 9: 7–29
13 Thunell R C, Qingmin M, Calvert S E, et al. Glacial-Holocene biogenic sedimentation patterns in the South China Sea: Productivity variations and surface water pCO$_2$. Paleoceanography, 1992, 7: 143–162
14 Linsley B K, Dunbar R B. The late Pleistocene history of surface water δ^{13}C in the Sulu Sea: Possible relationship to Pacific deepwater δ^{13}C changes. Paleoceanography, 1994, 9: 317–340
15 Li T, Liu Z, Hall M A, et al. A broad deglacial δ^{13}C minimum event in planktonic foraminiferal records in the Okinawa Trough. Chinese Sci Bull, 2002, 47: 599–603
16 Pena L, Cacho I, Ferretti P, et al. El Niño-Southern Oscillation-like variability during glacial terminations and interlatitudinal teleconnections. Paleoceanography, 2008, 23: PA3101, doi:10.1029/2008PA001620
17 Loubere P, Richaud M, Mireles S. Variability in tropical thermocline nutrient chemistry on the glacial/interglacial timescale. Deep-Sea Res Pt II, 2007, 54: 747–761
18 Stott L, Timmermann A, Thunell R. Southern hemisphere and deep-sea warming led deglacial atmospheric CO_2 rise and tropical warming. Science, 2007, 318: 435–438
19 Sarmiento J L, Gruber N, Brzezinski M A, et al. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature, 2004, 427: 56–60
20 Jian Z, Wang P, Saito Y, et al. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. Earth

Planet Sci Lett, 2000, 184: 305–319

21 Li T, Liu Z, Hall M A, et al. Heinrich event imprints in the Okinawa Trough: Evidence from oxygen isotope and planktonic foraminifera. Palaeogeogr Palaeoclimatol Palaeoecol, 2001, 176: 133–146

22 Chang F, Li T, Zhuang L, et al. A Holocene paleotemperature record based on radiolaria from the northern Okinawa Trough (East China Sea). Quat Int, 2008, 183: 115–122

23 Bostock H C, Opdyke B N, Gagan M K, et al. Carbon isotope evidence for changes in Antarctic Intermediate Water circulation and ocean ventilation in the southwest Pacific during the last deglaciation. Paleoceanography, 2004, 19: PA4013, doi:10.1029/2004PA001047

24 Kim Y Y, Qu T, Jensen T, et al. Seasonal and interannual variations of the North Equatorial Current bifurcation in a high-resolution OGCM. J Geophys Res, 2004, 109: C03040, doi:10.1029/2003JC002013

25 Qu T D, Lindstrom E J. Northward intrusion of Antarctic Intermediate Water in the western Pacific. J Phys Oceanogr, 2004, 34: 2104–2118

26 Qiu B, Lukas R. Seasonal and interannual variability of the North Equatorial Current, the Mindanao Current, and the Kuroshio along the Pacific western boundary. J Geophys Res, 1996, 101: 12315–12330

27 Qu T D, Lukas R. The bifurcation of the North Equatorial Current in the Pacific. J Phys Oceanogr, 2003, 33: 5–18

28 Yaremchuk M, Qu T D. Seasonal variability of the large-scale currents near the coast of the Philippines. J Phys Oceanogr, 2004, 34: 844–855

29 Sawada K, Handa N. Variability of the path of the Kuroshio ocean current over the past 25000 years. Nature, 1998, 392: 592–595

30 Toggweiler J R, Dixon K, Broecker W S. The Peru upwelling and the ventilation of the South Pacific thermocline. J Geophys Res, 1991, 96: 20467–20497

31 Thompson P. Planktonic foraminifera in the western north Pacific during the past 150 000 years: Comparison of modern and fossil assemblages. Palaeogeogr Palaeoclimatol Palaeoecol, 1981, 35: 241–279

32 Reimer P J, Baillie M G L, Bard E, et al. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50000 years cal BP. Radiocarbon, 2009, 51: 1111–1150

33 Bard E. Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: Paleoceanographic implications. Paleoceanography, 1988, 3: 635–645

34 Spero H J, Mielke K M, Kalve E M, et al. Multispecies approach to reconstructing eastern equatorial Pacific thermocline hydrography during the past 360 kyr. Paleoceanography, 2003, 18: 1022, doi:10.1029/2002PA000814

35 Ninnemann U S, Charles C D. Regional differences in Quaternary Subantarctic nutrient cycling: Link to intermediate and deep water ventilation. Paleoceanography, 1997, 12: 560–567

36 Shackleton N J, Hall M A, Line J, et al. Carbon isotope data in core V19-30 confirm reduced carbon dioxide concentration in the ice age atmosphere. Nature, 1983, 306: 319–322

37 Curry W B, Crowley T J. The δ^{13}C of equatorial Atlantic surface waters: Implications for Ice Age $p\mathrm{CO}_2$ levels. Paleoceanography, 1987, 2: 489–517

38 Monnin E, Indermuhle A, Dallenbach A, et al. Atmospheric CO_2 concentrations over the last glacial termination. Science, 2001, 291: 112–114