Article **Chinese Science Bulletin**

Oceanology

October 2012 Vol.57 No.30: 3917–3922
doi: 10.1007/s11434-012-5276-y

Paleoproductivity variations in the southern Okinawa Trough since the middle Holocene: Calcareous nannofossil records

ZHAO JingTao[1,2,3], LI TieGang[1*], LI Jun[2] & HU BangQi[2,3]

[1] *Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China;*
[2] *Key Laboratory of Marine Hydrocarbon Resource and Geology, Ministry of Land and Resources, Qingdao Institute of Marine Geology, Qingdao 266071, China;*
[3] *Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*

Received February 27, 2012; accepted April 27, 2012; published online June 22, 2012

Based on 17 AMS^{14}C age data, we reconstructed high-resolution records of sea surface primary productivity (PP) in the southern Okinawa Trough (MD05-2908) over the last 6.8 ka BP using the calcareous nannofossil carbon isotope and the relative percentage contents of *Florisphaera profunda* indexes. The underlying mechanism controlling the sea surface PP was then discussed. The sea surface PP, indicated by the coccolith δ^{13}C and %Fp conversional equations, decreased with some fluctuations since 6.8 ka BP. This decrease may be connected to the decreased terrigenous input resulting from the reduced East Asian Summer Monsoon (EASM) precipitation. Both the periods of 4–2 ka BP (PME) and 6.8–4.8 ka BP were characterized by relatively higher PP. The former was mainly controlled by the weakening of the Kuroshio Current, whereas the latter mainly resulted from the greater terrigenous input associated with the stronger EASM.

middle Holocene, the southern Okinawa Trough, primary productivity, calcareous nannofossil

Citation: Zhao J T, Li T G, Li J, et al. Paleoproductivity variations in the southern Okinawa Trough since the middle Holocene: Calcareous nannofossil records. Chin Sci Bull, 2012, 57: 3917–3922, doi: 10.1007/s11434-012-5276-y

Relative to the ice volume changes of the high latitudes of the Northern Hemisphere, the process of low-latitude tropical influence on global climate change is mainly reflected in the controlling effects of the primary productivity of surface seawater on the global carbon cycle [1]. The CO_2 in the atmosphere is pumped into the seabed by sea surface phytoplankton through photosynthesis, and this process plays a critical role in regulating the global carbon cycle [2]. The Okinawa Trough, located under the main axis of the Kuroshio Current, has maintained a continuous sediment rate since the Late Quaternary. The high temperature, high salinity and oligotrophic Kuroshio water strongly influences the upper water structure and sea surface PP of this area. The terrigenous input from the East China Sea shelf associated with the East Asian Summer Monsoon (EASM) also impacts the sediments of the Okinawa Trough. Many studies have focused on the evolution of the paleoproductivity of various areas of the Okinawa Trough since the Late Quaternary using different proxies, such as biomarkers [3,4], biogenic silica and organic carbon [5,6] and benthic foraminifera [7,8].

The high sediment rate of the southern Okinawa Trough has attracted the attention of many scholars [9–11]. Core ODP-1202, taken from the southern Okinawa Trough, has an average sediment rate of 325 cm/ka [12]. In this paper, the studied core MD05-2908 has a higher average sedimentation rate of 500 cm/ka since the last 6.8 ka BP. Many paleoenvironmental results have been presented from this core. Nan et al. [3] evaluated the paleoproductivity and interpreted the climatic-induced controlling factors over the past 7000 a. Li et al. [13] analyzed sediment diatoms to infer climate and paleoenvironmental changes over the past 1000 a. Li et al. [14] discussed the changes of sediment transport and source supply over the last 6.8 ka BP. As the main primary producers in the ocean, coccolithophores' vital activities are closely related to ocean hydrological

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

conditions and nutrient levels [15,16]. Thus, calcareous nannofossils in the sediments are good carriers of the PP and the upper water structure. In this study, we discussed the sea surface PP changes in the southern Okinawa Trough over the last 6.8 ka BP based on the calcareous nannofossil proxies in core MD05-2908.

1 Study area

The southern Okinawa Trough region (Figure 1) has a typical subtropical monsoonal climate, where the hydrological conditions are strongly influenced by temperature, humidity and atmospheric circulation [19]. The Kuroshio Current, originating from the equatorial Pacific Ocean, flows into the Okinawa Trough through the I-Lan Ridge, transporting large amounts of heat and vapor to the mid-latitude North Pacific [20]. The sea surface temperature (SST) in the southern Okinawa Trough is obviously affected by the Kuroshio Current, with the strongest part of the Kuroshio Current accompanied by higher SSTs. The seasonal changes of the southern Okinawa Trough sea surface salinity (SSS) and the PP are affected by the monsoon process. When a stronger summer monsoon occurs, the enormous amount of runoff from the Yangtze River and Taiwan rivers induces a large amount of freshwater and nutrient input to the southern Okinawa Trough, with a resultant SSS decrease and PP increase [21].

The main sediment source of the southern Okinawa Trough is eroded material from Taiwan mountains due to abundant summer rainfall [22]. Approximately 6–9 Mt sediments empty into the South Okinawa Trough each year through the Lanyang River of northern Taiwan. This sedimentation is usually shown as a pulse input controlled by abrupt climate events, such as earthquakes, typhoons and floods [23]. In addition, the Yangtze River inputs 240–260 Mt sediments to the East China Sea each year [24], and a small portion of suspended material from the Yangtze River and shelf deposits move into the southern Okinawa Trough through the coastal current [25]. The southeast side of Cotton Valley and the North Mien-Hua Canyon is the transportation channel of sediment from the East China Sea shelf to the southern Okinawa Trough [26].

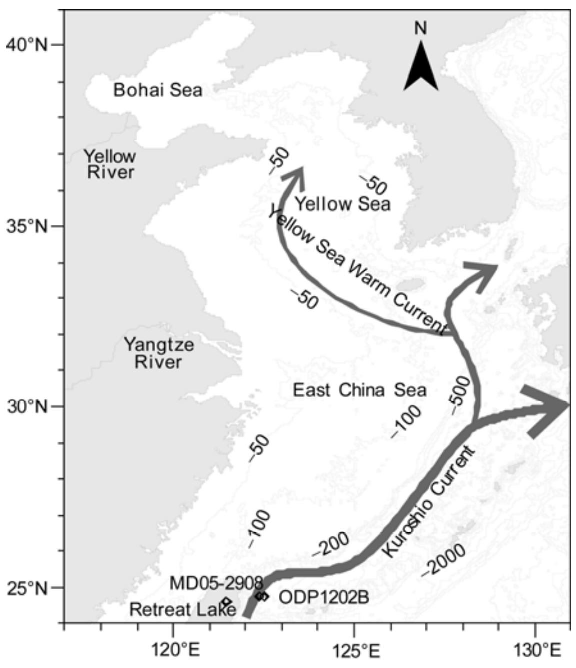

Figure 1 Location map of core MD05-2908 and the other cores discussed in this study. ODP-1202 [12], Retreat Lake [17] and Kuroshio Current [18].

2 Materials and methods

The piston core MD05-2908 used in this study was recovered from the southern Okinawa Trough (northeast of Taiwan, 24°48.04'N, 122°29.35'E, water depth 1276 m) during the IMAGES XIV, MD-147-Marco Polo 2 cruise of the R/V Marion Dufresne of the French Polar Institute (IPEV) (Figure 1). The 34.16-cm-long core is mainly composed of homogenous dark gray hemipelagic clay and fine silt-sized sediments without evidence of turbidites or mass redeposition. The 0–979 cm section is dark gray clay, and the 979–3416 cm section is black-grey silty clay containing a plurality of coarse sand layers.

A stable isotope analysis of the coccoliths was performed with 420 samples at 8 cm intervals. For the experimental methods, refer to Liu et al. [27]. After processing, the samples were analyzed using a MAT252 gas mass spectrometer at Institute of Earth Environment, Chinese Academy of Sciences. The analysis precision for coccolith δ^{13}C was 0.08×10^{-3}. The relative percentages of the lower photic calcareous nannofossil species *F. profunda* were analyzed using 203 samples at 10–18 cm intervals. Qualitative analysis was performed at 1600× magnification using a Leica polarizing microscope at the Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences. Counts and identifications were performed on permanent slides mounted with Canada balsam. At least 300 coccoliths were counted for each slide, and the relative percentages of *F. profunda*: *F.p%*=(number of *F. profunda*/total coccolith number)×100.

The age model of core MD05-2908 was obtained by linearly interpolating between 17 ^{14}C dating points [14]. The 34.16-cm-long core spans a continuous paleoceanographic history of the past 6790 cal a BP and provides a high-resolution record of the paleoclimate change since the middle Holocene. The sedimentation rates varied widely, from 0.18 to 2.12 cm/a, with an average of 0.50 cm/a. The average resolution for the coccolith stable isotope analysis was higher than 17 a, and 34 a for the calcareous nannofossil analysis respectively.

3 Results and discussion

3.1 Variations of *F.p%* and coccolith $\delta^{13}C$ in core MD05-2908 over the last 6.8 ka BP

As shown in Figure 2(a) and (b), the *F.p%* and coccolith $\delta^{13}C$ changed from 30% to 58% and from −2.34‰ to −0.14‰, with average values of 44% and −0.90‰, respectively. The *F.p%* was lower during 6.8–4.8 ka BP, with an average value of 42%, and the coccolith $\delta^{13}C$ was higher (average value of −0.66‰) during this stage. After 4.8 ka BP, the coccolith $\delta^{13}C$ increased first, then decreased and increased again, contrary to the variations of *F.p%*. The coccolith $\delta^{13}C$ showed relatively higher values during 4–2 ka BP, with an average value of −0.80‰, which is slightly less than at the 6.8-4.8 ka BP stage. The *F.p%* was relatively lower during 4–2 ka BP, with an average value of 44%.

3.2 PP variations in the southern Okinawa Trough over the last 6.8 ka BP

Coccolithophorids grow and calcify only in the euphotic layer and therefore exhibit surface water isotopic characteristics. In the mid-1970s, scholars [28] explored the potential applications of the stable isotope composition of coccolithophorids in paleoceanographic studies. Goodney et al. [29] proposed that sea surface PP could influence the $\delta^{13}C$ of coccoliths from the study of carbon isotopes of recent coccoliths from Indian Ocean core-tops. Recent results of Quaternary sediments from the southern South China Sea, the western Pacific warm pool and the western Philippine Sea showed that coccolith $\delta^{13}C$ could qualitatively reflect the sea surface PP, and lower $\delta^{13}C$ values indicate lower PP values [27,30–32].

The coccolithophore *F. profunda* is widely distributed in

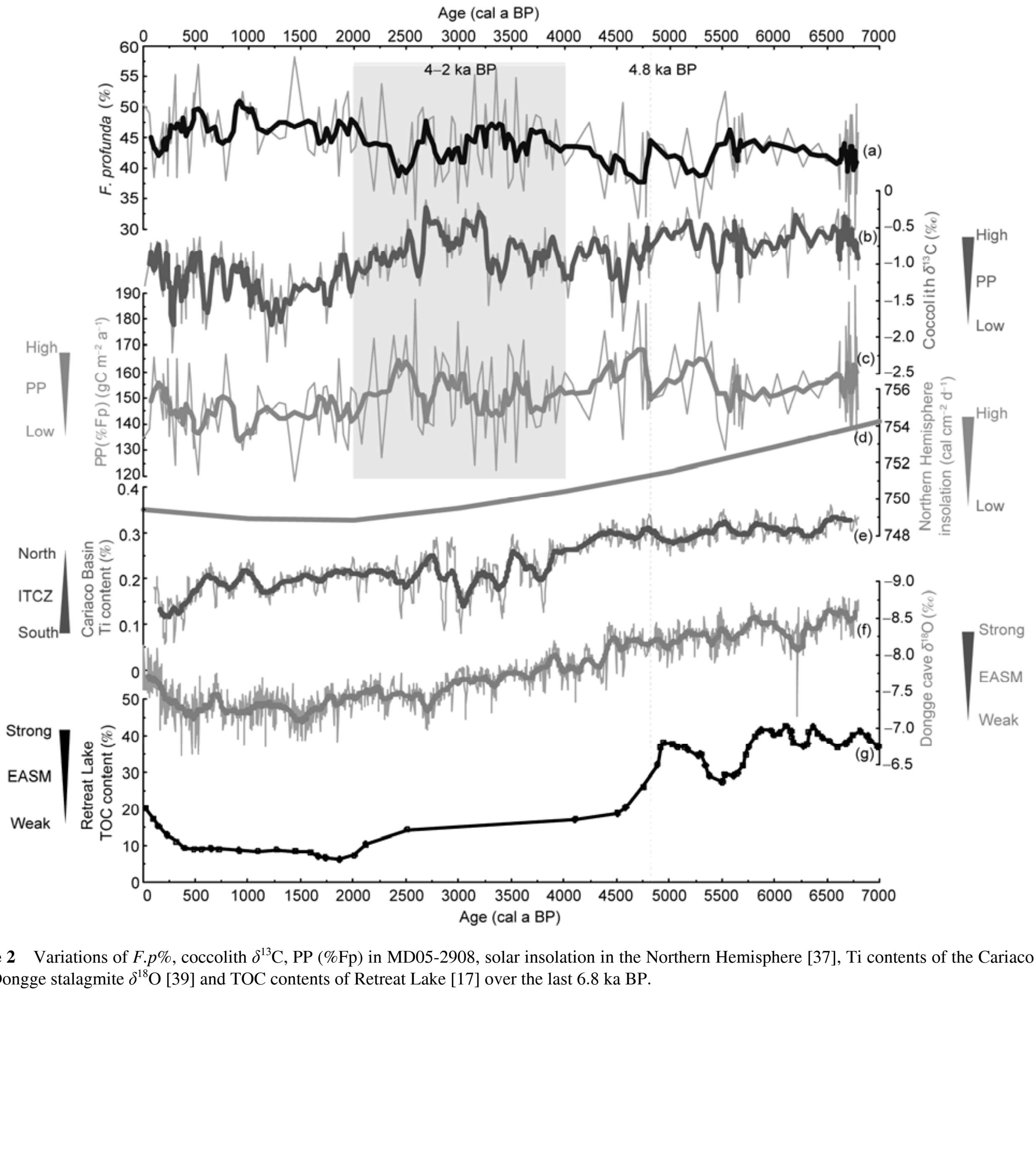

Figure 2 Variations of *F.p%*, coccolith $\delta^{13}C$, PP (%Fp) in MD05-2908, solar insolation in the Northern Hemisphere [37], Ti contents of the Cariaco Basin [38], Dongge stalagmite $\delta^{18}O$ [39] and TOC contents of Retreat Lake [17] over the last 6.8 ka BP.

the lower euphotic zone of the tropical-subtropical ocean [33], and its relative abundance is used to reconstruct oceanic primary production [34,35]. The relationship between the relative abundance of *F. profunda* and sea surface PP has already been quantified by Beaufort et al. [34] with the equation PP=617−[279×log(*F.p*%+3)], and the latitudinal range is the main limiting condition. Beaufort et al. [35] have successfully applied this equation to the Indian Ocean and the Pacific Ocean. Although core MD05-2908 (24.8°N) does not belong to the latitudinal range (20°S–20°N) of this equation, the southern Okinawa Trough has the characteristic of a strong, warm water source, so we tried to use the conversion equation to reconstruct the PP records. The PP (%Fp) value of the core top samples is 135 gC m^{-2} a^{-1}, which is very similar to the estimated summer surface PP (131±18 gC m^{-2} a^{-1} deduced from the measured data [21].

The PP(%Fp) changes between 118–193 gC m^{-2} a^{-1}, with anaverage value of 151 gC m^{-2} a^{-1} (Figure 2(c)). The PP(%Fp) was relatively higher (average of 156 gC m^{-2} a^{-1} during 6.8–4.8 ka BP, which is consistent with the higher PP indicated by coccolith δ^{13}C. After 4.8 ka BP, the PP (%Fp) increased first, then decreased and increased again, similar to the PP variations reflected by coccolith δ^{13}C. It is noteworthy that both PP proxies showed high levels between 4–2 ka BP, corresponding to the Pulleniatina Minimum Event (PME) [10,36]. As shown in Figure 2(b) and (c), the PP reflected by the coccolith δ^{13}C and *F.p%* conversion equation in core MD05-2908 generally showed a fluctuating trend since 6.8 ka BP.

3.3 The impact mechanism of PP variations of the southern Okinawa Trough over the last 6.8 ka BP

Previous studies found that the sea surface PP evolution of the northern and middle Okinawa Trough is closely connected to the terrigenous input for the last 10 ka, and even the last 100 ka, and it may be affected by the EASM [40,41]. The core MD05-2908, located at the southern end of the Okinawa Trough, faces the Lanyang River delta of western Taiwan, north of which are the Jilong Valley, the Cotton Canyon and the north Cotton Canyon. These topographical features cause this area to easily accept terrigenous input material from the East China Sea shelf and Taiwan. Mineral and geochemistry indexes from adjacent core ODP1202 demonstrated that the provenance of this area was mainly the northeastern rivers of Taiwan since the Holocene [42]. Modern sedimentary dynamical observations showed that a large amount of eroded materials of Taiwan mountains was transported to the southern Okinawa Trough during the summer season [22]. In addition, a large amount of terrigenous materials was transported to the southern Okinawa Trough by the Taiwan rivers during the stronger EASM stage, which can induce stronger turbulence of the upper waters and the shallower nutricline eventually increasing the PP. Therefore, we believe that the PP records of the MD05-2908 core are more sensitive to the changes of the EASM than other areas of the Okinawa Trough.

In the Mid-Holocene, the summer insolation of the Northern Hemisphere increased, leading to enhancement of seasonal contrast [43]. The numerical simulation results showed that the pressure gradient of the land and sea was enhanced by the strengthened Asian low pressure and the Pacific high pressure during the Mid-Holocene summer, which induced the stronger EASM [44]. In the Northern Hemisphere, the solar radiation of the Late Holocene decreased relative to the mid-Holocene (Figure 2(d)) [37], which should have weakened the capacity of pulling the ITCZ off the equator, inducing the southward shifts in the mean latitude of the ITCZ (Figure 2(e)). The EASM also weakened (Figure 2(f)) [39]. The TOC contents of Retreat Lake in Taiwan, near MD05-2908, indicated that the East Asian monsoon rainfall of the late Holocene was obviously lower than that of the Mid-Holocene (Figure 2(g)) [17]. The characteristics of the gradually weakening EASM since the Mid-Holocene have been recorded in many areas of the Asian monsoon region, such as the peat records of southern and northeastern China [45,46]; the stalagmite δ^{18}O records of Dongge cave in southern China and Shennongjia cave in central China [47,48]; and the pollen records of the Guangdong Huguang Maar Lake [49]. The EASM has weakened since the Late Holocene, reducing the terrigenous input of Taiwan rivers, and the upper water structure has become stable, resulting in the lower PP of this area. Our PP proxies of MD05-2908, including coccolith δ^{13}C and PP (%Fp), shows that the generally descending trend since the last 6.8 ka BP is consistent with the theory mentioned above.

The southern Okinawa Trough is located at the corner where the Kuroshio Current flows into the Okinawa Trough, and the hydrological conditions of the upper water are obviously influenced by the Kuroshio Current. The Kuroshio Current, originating from the Northern Equatorial Current, carries large amounts of high-temperature, high salinity and oligotrophic water, which can induce higher SSTs, a deeper nutricline and thermocline and a stronger PP.

The PP reflected by the coccolith δ^{13}C and *F.p%* conversion equation in core MD05-2908 showed high levels between 4–2 ka BP (Figure 2(b) and (c)), corresponding to the PME [10,36,50]. The weakening of the Kuroshio Current, representing the weakening of the Northern Equatorial Current and the trade winds over the equatorial Pacific Ocean, could induce the outbreak of El Niño. Geoarchaeological evidence from Peru indicates that ENSO activity strengthened after ~5 ka BP [51]. Storm deposition records from southwestern Ecuador proved that ENSO began in ~5 ka BP and a high-frequency of El Niño events appears at about 3.5–2.6 ka BP [52]. The SST gradient between the equatorial western and eastern Pacific of the Holocene reconstructed by foraminifera Mg/Ca has decreased since 4 ka BP, indicating the high frequency of El Niño events [53]. The SST of the tropical western Pacific dropped by 1.6°C from 5 to 2 ka BP [54], and the SST gradient between the equatorial western and eastern Pacific decreased, suggesting the prevalence of El Niño events. During El Niño, the interaction of the ocean-atmosphere induces the southern movement of the ITCZ [55], resulting in the weakening of the EASM. The weakening of the EASM during 4–2 ka BP is reflected in many records of the Asian monsoon regions, such as the intermittent deposition of Retreat Lake in Taiwan during 4.5–2.1 ka BP [17], the intermittent growth of the stalagmites of the northern Oman Hoti cave during 5.2–2.5 ka BP [56] and the low $\delta^{18}O$ values of the Shennongjia stalagmites in Hubei during 4.4–2.1 ka BP [57].

As discussed above, in the southern Okinawa Trough, the main controlling factors of the relatively higher PP during 4–2 ka BP is the weakening of the Kuroshio Current, not the reduced terrigenous inputs caused by the weakened EASM. During 6.8–4.8 ka BP, both PP proxies (coccolith $\delta^{13}C$ and PP (%Fp)) show higher values than those during 4–2 ka BP. As shown in Figure 2(d)–(g), the solar insolation is higher, the location of ITCZ is more northward and terrigenous inputs caused by the EASM are greater during 6.8–4.8 ka BP compared with during 4–2 ka BP. However, the long-chain alkenone data of MD05-2908 show that the SST during 6.8–4.8 ka BP is higher than that during 4–2 ka BP [58]. Previous studies have also demonstrated that the Kuroshio Current was stronger in the Mid-Holocene than in the Late Holocene [10,36,59]. This result shows that, compared with 4–2 ka BP, the relatively higher PP during 6.8–4.8 ka BP was mainly controlled by stronger terrigenous inputs caused by the strengthened EASM, and the effects of the Kuroshio Current are not obvious.

4 Conclusions

Based on 17 AMS^{14}C age data, we reconstructed high-resolution sea surface PP variations in the southern Okinawa Trough over the last 6.8 ka BP using the coccolith $\delta^{13}C$ and *F.p%* conversion equation indexes. The PP showed a fluctuating decreasing trend since 6.8 ka BP, which was consistent with the reduced terrigenous inputs caused by the weakened EASM. The main controlling factor of the higher PP during 4–2 ka BP was the weakening of the Kuroshio Current. Compared with 4–2 ka BP, the relatively higher PP during 6.8–4.8 ka BP was mainly controlled by stronger terrigenous inputs caused by the strengthened EASM.

The authors thank two anonymous reviewers for the constructive reviews to this paper. This work was supported by the Pilot Project of the Knowledge Innovation Program of Chinese Academy of Sciences (*KZCX2-YW-221*) *and the National Natural Science Foundation of China* (*40906033 and 40976036*) *and the Open Foundation of Key Laboratory of Marginal Sea Geology, Chinese Academy of Sciences* (*MSGL09-11 and MSGL12-01*).

1 Wang P X. Ice and carbon in climate evolution (in Chinese). Earth Sci Front, 2002, 9: 85–93
2 Archer D, Winguth A, Lea D, et al. What caused the glacial/interglacial atmospheric pCO_2 cycles? Rev Geophys, 2000, 38: 159–189
3 Nan Q Y, Li T G, Chen J X, et al. Paleoproductivity variation and its correlation with climate changes: An approachoflong long-chain alkenone (in Chinese). Quat Sci, 2008, 28: 482–490
4 Xing L, Zhao M X, Zhang H L, et al. Biomarker reconstruction of phytoplankton productivity and community structure changes in the middle Okinawa Trough during the last 15 ka. Chin Sci Bull, 2008, 53: 2552–2559
5 Huang X H, Wang R J, Jian Z M, et al. Responses of sea surface temperature and productivity to the changes of the Kuroshio Current in the northern Okinawa Trough during the Holocene (in Chinese). Adv Earth Sci, 2009, 24: 652–661
6 Dou Y G, Yang S Y, Tang M, et al. Using biogenic components to decipher the terrigenous input and paleoenvironmental changes over the last 28 ka in the middle Okinawa Trough (in Chinese). Quat Sci, 2011, 31: 236–243
7 Jian Z M, Li B H, Pflaymann U, et al. Late Holocene cooling event in the western Pacific. Sci China Ser D-Earth Sci, 1996, 39: 543–550
8 Li T G, Xiang R, Sun R T, et al. Benthic foraminifera and bottom water evolution in the middle-Southern Okinawa Trough during the last 18 ka. Sci China Ser D-Earth Sci, 2005, 48: 805–814
9 Jian Z M, Chen R H, Li B H. Deep-sea benthic foraminiferal record of the paleoceanography in the Southern Okiniwa Trough over the last 20000 years. Sci China Ser D-Earth Sci, 1996, 39: 551–560
10 Li B H, Jian Z M, Wang P X. *Pulleniatina obliquiloculata* as a paleoceanographic indicator in the southern Okinawa Trough during the last 20000 years. Mar Micropaleontol, 1997, 32: 59–69
11 Li T G, Liu Z X, Hall M A, et al. Heinrich event imprints in the Okinawa Trough: Evidence from oxygen isotope and planktonic foraminifera. Palaeogeogr Palaeoclmatol Palaeoecol, 2001, 176: 133–146
12 Wei K Y. Synthesis: Site 1202-Late Quaternary sedimentation and paleoceanography in the Southern Okinawa Trough. 2006
13 Li D L, Jiang H, Li T G, et al. Late Holocene paleoenvironmental changes in the southern Okinawa Trough inferred from a diatom record. Chin Sci Bull, 2011, 56: 1131–1138
14 Li C S, Jiang B, Li A C, et al. Sedimentation rates and provenance analysis in the Southwestern Okinawa Trough since the mid-Holocene. Chin Sci Bull, 2009, 54: 1234–1242
15 Okada H, Wells P. Late Quaternary nannofossil indicators of climate change in two deep-sea cores associated with the Leeuwin Current off Western Australia. Palaeogeogr Palaeoclmatol Palaeoecol, 1997, 131: 413–432
16 Beaufort L, De Garidel-Thoron T, Linsley B K, et al. Biomass burning and oceanic primary production estimates in the Sulu Sea area over the last 380 kyr and the East Asian monsoon dynamics. Mar Geol, 2003, 201: 53–65
17 Selvaraj K, Arthur Chen C T, Lou J Y, et al. Holocene weak summer East Asian monsoon intervals in Taiwan and plausible mechanisms. Quat Int, 2011, 229: 57–66
18 Ijiri A, Wang L J, Oba T, et al. Paleoenviromental changes in the northern area of the East China Sea during the past 42000 years. Palaeogeogr Palaeoclmatol Palaeoecol, 2005, 219: 239–261
19 Lee H J, Chao S Y. A climatological description of circulation in and around the East China Sea. Deep-Sea Res Part II, 2003, 50: 1065–1084
20 Hsin Y C, Wu C R, Shaw P T. Spatial and temporal variations of the Kuroshio east of Taiwan, 1982–2005: A numerical study. J Geophys Res, 2008, 113: C04002
21 Gong G C, Shiah F K, Liu K K, et al. Spatial and temporal variation of chorophyll *a*, primary productivity and chemical hydrography in the southern East China Sea. Cont Shelf Res, 2000, 20: 411–436
22 Hsu S C, Lin F J, Jeng W L, et al. Observed sediment fluxes in the southwesternmost Okinawa Trough enhanced by episodic events: Flood runoff from Taiwan rivers and large earthquakes. Deep-Sea Res Part I, 2004, 51: 979–997
23 Jeng W L, Lin S, Kao S J. Distribution of terrigenous lipids in marine

sediments off northeastern Taiwan. Deep-Sea Res Part II, 2003, 50: 1179–1201
24 Liu J, Xu K, Li A, et al. Flux and fate of Yangtze River sediment delivered to the East China Sea. Geomorphol, 2007, 85: 208–24
25 Liu K, Peng T, Shaw P, et al. Circulation and biogeochemical processes in the East China Sea and the vicinity of Taiwan: An overview and a brief synthesis. Deep-Sea Res Part II, 2003, 50: 1055–1064
26 Hung J J, Lin C S, Hung G W, et al. Lateral transport of lithogenic particles from the continental margin of the southern East China Sea. Estua Coast Shelf S, 1999, 49: 483–499
27 Liu C L, Cheng X R, Wang R J, et al. Oxygen and carbon isotope records of Quaternary calcareousnannofossils from the Western Pacific warm pool and their palaeoceanographical significance (in Chinese). Earth Sci, 2005, 30: 559–603
28 Margolis S V, Kroopnick P M, Goodney D E, et al. Oxygen and carbon isotopes from calcareous nannofossils as paleoceanographic indicators. Science, 1975, 189: 555–557
29 Goodney D E, Margolis S V, Dudley W C, et al. Oxygen and carbon isotopes of recent calcareous nannofossils as palaeoceanographic indicators. Mar Micropaleontol, 1980, 5: 31–42
30 Liu C L, Cheng X R, Zhu Y H, et al. Oxygen and carbon isotope records of calcareous nannofossilsfor the past 1 Ma in the southern South China Sea. Chin Sci Bull, 2002, 47: 798–803
31 Zhao J T, Li T G, Chang F M, et al. Oxygen and carbon isotope records of calcareous nannofossilsfrom the West Philippine Sea during the Last 190 ka (in Chinese). Earth Sci, 2008, 33: 183–189
32 Liu C, Wang P, Tian J, et al. Coccolith evidence for Quaternary nutricline variations in the southern South China Sea. Mar Micropaleontol, 2008, 69: 42–51
33 Okada H, Honjo S. The distribution of oceanic coccolithophorids in the Pacific. Deep-Sea Res Part I, 1973, 20: 355–364
34 Beaufort L, Lancelot Y, Camberlin P, et al. Insolation cycles as a major control of Equatorial Indian Ocean primary production. Science, 1997, 278: 1451–1454
35 Beaufort L, Garidel-Thoron T, MixA C, et al. ENSO-like forcing on oceanic primary production during the Late Pleistocene. Science, 2001, 293: 2440–2444
36 Jian Z, Wang P, Saito Y, et al. Holocene variability of the Kuroshio current in the Okinawa Trough, northweatern Pacific ocean. Earth Planet Sci Lett, 2000, 184: 305–319
37 Berger A, Louter M F. Insolation values for the climate of the last 10 million years. Quat Sci Rev, 1991, 10: 297–317
38 Haug G H, Hughen K A, Sigman D M, et al. Southward migration of the Intertropical Convergence Zone through the Holocene. Science, 2001, 293: 1304–1308
39 Wang Y J, Cheng H, Edwards R L, et al. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. Science, 2005, 308: 854–857
40 Chang Y P, Wang W L, Chen M T. The last 100000 year's palaeoenvironmental changes inferred from the diatom assemblages of core MD012404 from the Okinawa Trough, East China Sea. J Quat Sci, 2009, 24: 890–901
41 Chang F M, Li T G, Zhuang L H, et al. The environmental anomalies in the northeastern East China Sea since about 3000 cal a BP and its possible relation to El Niño activity in the Holocene (in Chinese). Quat Sci, 2008, 28: 472–481
42 Diekmann B, Hofmann J, Henrich R, et al. Detrital sediment supply in the southern Okinawa Trough and its relation to sea-level and Kuroshio dynamics during the late Quaternary. Mar Geol, 2008, 255: 83–95
43 Kutzbach J E. Monsoon climate of the early Holocene: Climate experiment with the Earth's orbital parameters for 9000 years ago. Science, 1981, 214: 59–61
44 Zhou B T, Zhao P. Inverse correlation between ancient winter and summer monsoons in East Asia? Chin Sci Bull, 2009, 54: 3760–3767
45 Zhou W, Yu X, Jull A J T, et al. High-resolution evidence from southern China of an early Holocene optimum and a mid-Holocene dry event during the past 18000 years. Quat Res, 2004, 62: 39–48
46 Hong Y T, Hong B, Lin Q H, et al. Inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the last 12000 years and paleo-El Niño. Earth Planet Sci Lett, 2005, 231: 337–346
47 Dykoski C, Edwards R, Cheng H, et al. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth Planet Sci Lett, 2005, 233: 71–86
48 Shao X H, Wang Y J, Cheng H, et al. Long-term trend and abrupt events of the Holocene Asian monsoon inferred form a stalagmite $\delta^{18}O$ record from Shennongjia in Central China. Chin Sci Bull, 2006, 51: 221–8
49 Wang S Y, Lü H Y, Liu J Q, et al. The early Holocene optimum inferred from ahigh-resolution pollen record of Huguangyan Maar Lake in southern China. Chin Sci Bull, 2007, 52: 2829–2836
50 Xiang R, Sun Y B, Li T G, et al. Paleoenvironmental change in the middle Okinawa Trough since the last deglaciation: Evidence from the sedimentation rate and planktonic foraminiferal record. Palaeogeogr Palaeoclmatol Palaeoecol, 2007, 243: 378–393
51 Sandweiss D H, Richardson J B, Reitz E J, et al. Geoarchaeological evidence from Peru for a 5000 years B.P.: Onset of El Niño. Science, 1996, 273: 1531–1533
52 Rodbell D T, Seltzer G O, Anderson D M, et al. A ~15000-year record of El Niño-driven alluviation in southwestern Ecuador. Science, 1999, 283: 516–520
53 Koutavas A, Demenocal P B, Olive G C, et al. Mid-Holocene El Niño-Southern Oscillation (ENSO) attenuation revealed by individual foraminifera in eastern tropical Pacific sediments. Geology, 2006, 34: 993
54 Stott L, Cannariato K, Thunell R, et al. Decline of surface temperature and salinity in the weatern tropical Pacific Ocean in the Holocene epoch. Nature, 2004, 431: 56–59
55 Gagan M K, Hendya E J, Haberleb S G, et al. Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño-Southern Oscillation. Quat Int, 2004, 118: 127–143
56 Fleitmann D, Burns S J, Mangini A, et al. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quat Sci Rev, 2007, 26: 170–188
57 Shao X H, Wang Y J, Cheng H, et al. Long-term trend and abrupt events of the Holocene Asian monsoon inferred from a stalagmite $\delta^{18}O$ record from Shennongjia in Central China. Chin Sci Bull, 2006, 51: 221–228
58 Nan Q Y. The Kuroshio Current variability and its responses to global high frequency climate events for the past 25 ka B.P. Dissertation for the Doctoral Degree. Beijing: Graduate University of Chinese Academy of Sciences, 2008. 38–40
59 Wang J, Saito Y, Oba T, et al. High-resolution records of thermocline in the Okinawa Trough since about 10000 a BP. Sci China Ser D-Earth Sci, 2001, 44: 193–200