Paleoenvironmental change in the middle Okinawa Trough since the last deglaciation: Evidence from the sedimentation rate and planktonic foraminiferal record

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Abstract

Well-dated, high-resolution records of planktonic foraminifera and oxygen isotopes from two sediment cores, A7 and E017, in the middle Okinawa Trough reveal strong and rapid millennial-scale climate changes since ~18 to 17 thousand years before present (kyr B.P.). Sedimentation rate shows a sudden drop at ~11.2 cal. kyr B.P. due to a rapid rise of sea-level after the Younger Dryas (YD) and consequently submergence of the large continental shelf on the East China Sea (ECS) and the retreat of the estuary providing sediment to the basin. During the last deglaciation, the relative abundance of warm and cold species of planktonic foraminifera fluctuates strongly, consistent with the timing of sea surface temperature (SST) variations determined from Mg/Ca measurements of planktonic foraminifera from one of the two cores. These fluctuations are coeval with climate variation recorded in the Greenland ice cores and North Atlantic sediments, namely Heinrich event 1 (H1), Bølling-Allerød (B/A) and YD events. At about 9.4 kyr B.P., a sudden change in the relative abundance of shallow to deep planktonic species probably indicates a sudden strengthening of the Kuroshio Current in the Okinawa Trough, which was synchronous with a rapid sea-level rise at 9.5-9.2 kyr B.P. in the ECS, Yellow Sea (YS) and South China Sea (SCS). The abundance of planktonic foraminiferal species, together with Mg/Ca based SST, exhibits millennial-scale oscillations during the Holocene, with 7 cold events (at about 1.7, 2.3-4.6, 6.2, 7.3, 8.2, 9.6, 10.6 cal. kyr BP) superimposed on a Holocene warming trend. This Holocene trend, together with centennial-scale SST variations superimposed on the last deglacial trend, suggests that both high and low latitude influences affected the climatology of the Okinawa Trough.

Keywords: Okinawa Trough, Last deglaciation, Holocene, Planktonic foraminifera, sedimentation rate, Kuroshio Current, Millennial- scale climate changes, Oxygen isotope

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1. Introduction

The last deglaciation and Holocene were characterized by a series of rapid, suborbital millennial-scale climate changes. The last deglaciation was punctuated by several high-frequency oscillations, for example the Bølling and Allerød warm phase (B/A), the Heinrich event 1 (H1) and Younger Dryas (YD) cold periods, or the Antarctic Cold Reversal (ACR) (Kiefer and Kienast, 2005). The ages, durations and characteristics of these climate events, however, were not globally uniform. In the circum-North Atlantic realm, the large warming associated with the last deglaciation was usually interrupted by a return to cold conditions, the YD event, occurring between about 12.8-11.6 kyr B.P. (e.g., Grootes et al., 1993; Bond et al., 1993; Dansgaard et al., 1993). Most temperature records from Antarctica and the Southern Ocean show an earlier interruption of their warming with the ACR starting around 14 kyr B.P. (Jouzel et al, 1995; Blunier et al, 1998; James et al, 2003). This asynchronous development of deglaciation sea surface temperature (SST) between the northern and southern hemisphere support the concept of the bipolar seesaw (Crowley, 1992; Broecker, 1998; Alley and Clark, 1999; Stocker, 2000). Recent high-resolution isotopic records obtained from East Antarctic cores further confirm that the overall deglacial pattern is asynchronous between Greenland and Antarctica (Steig et al, 1998; Watanabe et al, 2003; Morgan et al, 2002), but further suggest that the picture of a bipolar temperature seesaw might be too simple to describe deglacial changes. The Holocene is also characterized by millennial-scale climate change, seen in proxy records such as ice-rafted debris events in the subpolar North Atlantic (Bond et al., 1997, 2001), cooling events in the subtropical North Atlantic off West Africa (deMenocal et al., 2000) and Arabian Sea (Sirocko et al., 1996), and reduced rain fall episodes in Oman (Neff et al., 2001) and Dongge Cave (Dykoski et al,, 2005; Wang et al., 2005). Better understanding of the dynamic mechanics of these millennial-scale climate changes and the linkage between different components of the climate system requires obtaining high-resolution globally distributed oceanic records.

The East China Sea (ECS) is a typical marginal sea with one of the widest continental shelves in the world, and over which enormous amounts of freshwater are discharged from the Yangtze River. The Okinawa Trough, as the southeastern part of the ECS, is a typical curved basin behind the Ryukyu Arc of the northwestern Pacific (Figure 1). Its surface hydrography is strongly influenced by the East Asia monsoon (EAM), which shows a strong link with the high-latitude Northern Hemisphere climate on geologic time scales (e.g., Jian et al., 2000; Li et al., 2001; Sun et al., 2005). It is also connected to the tropics through the Kuroshio Current, which carries warm and hypersaline water flows northeastward along the edge of the continental shelf and then leaves the Okinawa Trough through the Tokara Strait (Figure 1). The path and volume transport of the Kuroshio Current are influenced by the EAM. The main axis of the Kuroshio Current shifts seasonally under the alternation influences between cold, dry winter monsoon winds and warmer

moist summer monsoon winds (Li, 1993). The northward transport of the Kuroshio is also influenced by the EAM, with more transport in summer than in winter (Kagimoto and Yamagata, 1997; Qu and Lukas, 2003; Qu et al., 2004). Kuroshio Current transport also varies on interannual time scales, with less transport during El Niño years and more during La Niña years, but in the modern ocean, seasonal variations are greater than those that occur on interannual times scales (Kim et al., 2004; Qu et al., 2004).

Previous studies from the Okinawa Trough showed that discrete palaeoclimatic events such as YD and H1 were recorded in the Okinawa Trough, and inferred variable influence of the Kuroshio Current during the Holocene (Jian et al., 2000; Li et al., 2001; Ujiié, et al., 1991; Ujiié and Ujiié, 1999; Ujiié, et al., 2003; Ijiri et al., 2005; Sun et al. 2005). However, the timing and duration of these millennial-scale climate changes are still unclear because there are few well-dated, multiple-proxy, high-resolution paleoceanographic records from this region. The best dated marine record of paired Mg/Ca and δ^{18}O from core A7 suggests that during the last deglaciation, surface hydrography of the Okinawa Tough was closely linked with North Atlantic climate, possibly through changes in the EAM (Sun et al., 2005). Tropical influence on the Okinawa Trough may have lead to differences between the amplitude and timing of changes in the Okinawa Trough and North Atlantic region. Here, we seek to confirm those conclusions with the addition of panktonic foraminiferal proxies from the same core and another core (E017), as well as provide new insights into the role of local sea level rise on the surface hydrography of the Okinawa Trough.

2. Material and methods

Gravity cores A7 (27º49.2´N, 126º58.7´E, water depth 1264 m) and E017 (26º34.45´N, 126º1.38´E, water depth 1826 m) were collected from the middle Okinawa Trough (Figure 1). Core A7 (4.5 m in length) consists of gray silty clay with an apparent ash layer at 1.02-1.1 m and several small turbidites at 1.10-1.20 m and 1.46-1.50 m whose extent is well constrained by sedimentological analysis (Sun et al., 2003). Core E017 (2.98 m in length) is also composed of gray silty clay with an obvious sand layer (coarse turbidite containing abundant foraminifera) at 2.46-2.48 m which shows clear boundaries to sediments above and below this layer (Xiang et al., 2003). A turbidite containing abundant volcanic glass is also found at 0.8-0.9 m and several small turbidites occurred at 2.51-2.66 m in core E017 (Figure 2). These small turbidites in cores A7 and E017 are composed mainly of clay silt and are less abundant in planktonic and benthic foraminifera, and only few foraminifers appeared in turbidite sediments at 2.51-2.66 m in core E017. The ash layer and its nether turbidites at 1.02-1.20 m in core A7 may be coeval with turbidites layer abundant in volcanic glass at 0.8-0.9 m in core E017 because the ash layer likely corresponds to the widespread tephra erupted from southern Kyushu in Japan (hereafter referred to as K-Ah tephra) (Marchida and Arai, 1978), which has also been identified from the northern and middle Okinawa Trough (Xu et al., 1999; Li et al., 2001; Ijiri et al., 2005). The tephra was

deposited at ~7.3 cal. kyr B.P. as indicated by both the AMS ^{14}C dating of terrestrial macrofossils and varve counts of the sediments in Lake Suigetsu (Kitagawa et al., 1995; Fukusawa et al., 1995). Other turbidites in cores A7 and E017 show no correlation.

Samples were taken at 2-cm interval for core A7 and 4-cm interval for core E017, and a total of 300 samples were analyzed for planktonic foraminifera and stable isotope in cores A7 and E017, respectively. Samples were oven dried at 60℃, then each sample (about 5 g dry weight) was soaked in distilled water for ~24 hours to disaggregate, and wet-sieved through a 63-μm sieve, then dried in the oven again. Planktonic foraminifers were picked out from the coarse fraction (> 150 μm) for faunal identification, stable isotope analysis and AMS^{14}C dating.

For planktonic foraminiferal analyses, counts were made on splits of more than 300 specimens larger than 150 μm. The average number of specimens counted for down-core samples is 796 for core A7 and 580 for core E017. To verify the reliability of splitting, 26 samples from core A7 were reanalyzed for planktonic foraminifera counting, and the results show very good reproducibility (see appendix). On the basis of the census data, the relative abundance of each planktonic foraminiferal species was computed.

Stable isotope analyses of core A7 were performed on planktonic foraminifers *G. ruber* and was reported previously (Sun et al., 2005). For Core E017, we picked shallow-dwelling planktonic foraminifers, *Globigerinoides sacculifer* (without sac)*,* test size ranging from 300 to 355 μm, for oxygen isotope analyses. The δ^{18}O values were measured on a SIRA mass spectrometer at Godwin Institute for Quaternary Research, University of Cambridge, UK. The analytical precisions of the samples are within ±0.08‰.

Accelerator mass spectrometry (AMS) ^{14}C dates were used to construct the chronologies of the two cores. All AMS ^{14}C dates were conducted on monospecific planktonic foraminifers *Neogloboquadrina dutertrei*. About 20 mg of shells of this species were picked out from the >150 μm fraction for the measurements. AMS dates of core A7 were reported previously (Sun et al., 2005). Seven horizons were dated in core E017, 3 were measured at the National Ocean Sciences Accelerator Mass Spectrometry (AMS) Facility, the Woods Hole Oceanographic Institution, USA, and 4 samples were dated at the Ministry of Education Key Laboratory of Heavy Ion Physics, Peking University, China (Table 1).

3. Results

3.1 Chronology

Fifteen AMS^{14}C dates were used to generate a high-resolution time scale for core A7 (Sun et al., 2005). In this paper, we adopt an age model using a 700-year surface-ocean reservoir age because it shows good correspondence with the age of K-Ah ash layer (Sun et al., 2005). Hence, all AMS ^{14}C ages in cores E017 were also converted to calendar years using the Caleb 5.0 program (available at http://radiocarbon.pa.qub.ac.uk/calib/) and a 700-year surface ocean reservoir

correction (Stuiver et al., 1998; Hughes et al., 2004) (Table 1). According to these dates, cores A7 and E017 both provide high-resolution sedimentary records since the last ~17-18 cal. kyr B.P. So far, core A7 provides the highest sample resolution among cores studied in the Okinawa Trough with detailed AMS^{14}C dates (sample resolution averagely 48 years in the last deglaciation and 115 years for the Holocene).

Compared to core A7, the age control points for core E017 are relatively sparse. There is also an apparently old AMS^{14}C age at 246-248 cm, a coarse turbidite containing abundant foraminifera, suggesting that most of the foraminifera in this layer may be of exotic origin. In order to get a detailed time scale for core E017, five additional age control points were obtained by lithological correlation and biostratigraphic correlation with core A7 (Figure 2). The ages of turbidites/ash layer at 1.02-1.20 m in core A7 was well constrained by two AMS^{14}C dates just above and below this layer, which were used to anchor age control points for the turbidite layer abundant in volcanic glass at 0.8-0.9 m in core E017. We arrived at two additional age control points for core E017 by this lithological correlation: about 7223 cal. yr B.P. at 0.8 m and 8580 cal. yr B.P. at 0.9 m (Figure 2). The distributions of planktonic foraminiferal species show in Fig. 2 are sufficiently similar to permit biostratigraphic correlation in cores A7 and E017. Three age control points were obtained through the comparisons of *Pulleniatina obliquiloculata*, *Gblobigerina bulloides* and *Neoglobquadrina pachyderma* (dex.), which give ages of about 4700 cal. yr B.P. at 0.55 m, 10305 cal. yr B.P. at 1.07 m and 11666 cal. yr B.P. at 1.39 m for core E017 (Figure 2). Thus, the age model of core E017 was constructed using the 5 relative age control points and AMS^{14}C dates.

3.2 Sedimentation rate

A piston core DGKS9603 (28°08.869′N, 127°16.238′E, water depth 1100 m) collected from the middle Okinawa Trough was previous studied (Li et al., 2001). According to age model of cores A7, E017 and DGKS9603, the sedimentation rate decreased at ~11.2 cal. kyr B.P. in the middle Okinawa Trough since the last ~18-17 cal. kyr B.P. (Figure 3). The sedimentation rate of core A7 decreased at a depth of 1.75 m, from 42.3 cm/kyr during the last deglaciation to 15.6 cm/kyr in the Holocene. The sedimentation rate of core E017 decreased at depth of 1.07 m, from 26.8 cm/kyr during the last deglaciation to 11.9 cm/kyr in the Holocene. The sedimentation rate of core DGKS9603 decreased at depth of 0.64 m, from 13.3 cm/kyr during the last deglaciation to 6.3 cm/kyr during the Holocene. In fact, this change in sedimentation rate was mainly caused by the sedimentation of non-biogenic materials, which are mainly composed of terrigenous materials. In core A7, the percentage of terrigenous matter (not shown) fluctuate at a range of 53.0-69.3%, except for the ash layer and turbidites whose content is higher than 70%. The content of terrigenous materials is high in the last deglaciation (64.3-69.3%) and low in the Holocene (53.0-67.2%).

3.3 Variations in the relative abundance of planktonic foraminiferal species

Both cores A7 and E017 contain reliable planktonic foraminiferal records except for turbidites at 2.46-2.48 and 2.51-2.66 m in core E017 which are likely to be less reliable in the foraminiferal record and are omitted from the core. The average abundance of planktonic foraminifera is 1361 specimens/g in core A7, and 765 specimens/g in core E017. Planktonic foraminifer are less abundant in core E017 than in core A7 due to the deeper water depth of core E017, which is near the modern carbonate lysocline (~1600-1700 m) in the Okinawa Trough (Chen et al., 1999; Xiang et al., 2001). According to planktonic foraminiferal fragmentation ratios in cores A7 and E017, strong carbonate dissolution only appeared after ~3 cal. kyr B.P. in the Okinawa Trough during the last 18000 years, suggesting that the modern shallow carbonate lysocline may be formed at that time (Li et al., 2005). The abundance of planktonic foraminifera greatly reduced since 3 cal. kyr B.P. in core E017 (averagely 212 specimens/g), which caused a slightly enrichment in dissolution resistant species *P. obliquiloculata* by selective preservation of foram tests. The foraminiferal assemblages in core E017 before 3 cal. kyr B.P., however, show no apparent influence of selective preservation.

The planktonic foraminifer assemblages in cores A7 and E017 are typical of the subtropical faunal province (Bé, 1977), and are dominated by *N. dutertrei*, *G. ruber*, *P. obliquiloculata*, *Globigerinita glutinata*, *G. bulloides* and *G. sacculifer*. Subarctic dominant species *N. pachyderma* (dex.), however, is abundant below 15 cal. kyr B.P., consistent with an influence of subarctic water in the middle Okinawa Trough at that time (Sun et al., 2005).

As noted above, relative abundances of planktonic foraminifera in the cores A7 and E017 show similar variations, as expected by their close proximity (Figure 4 and 5). Cold and cool water species (*N. pachyderma* (dex.), *Globigerina quinqueloba*, *Globorotalia inflata* and *N. dutertrei*) are dominant in the sediments that were deposited during the last deglaciation, showing a decreasing trend upward. These species show large fluctuations during the last deglaciation probably corresponding to the H1, YD and B/A periods (Figure 4). In contrast, the Holocene is dominated by warm water species of *G.ruber*, *G.sacculifer*, *G. glutinata* and *P. obliquiloculata*, which exhibit a slight increasing trend (Figure 5). Both warm and cold/cool water species show fluctuations at about 1.7, 2.3-4.6, 6.2, 7.3 and 8.2 cal. kyr BP in core A7. The period at 2.3-4.6 cal. kyr BP., the so-called *Pulleniatina* minimum event (PME), was characterized by a dramatic drop of *P. obliquiloculata* and a slight increase of *G. bulloides* and *N. dutertrei* in both cores. Another minimum of *P. obliquiloculata* is also found from ~15.3-16.8 cal. kyr B.P. (Figure 5), which corresponds well to the H1 event in the North Atlantic.

Previous studies suggest that planktonic foraminiferal species abundance has a close relation with the upper water thermal structure (Ravelo et al., 1990). When the depth of thermocline (DOT) shoals, the deep-dwelling species (*Globorotalia*, *N. dutertrei* and *N. pachyderma*) increase, while the shallow-dwelling species (*G.ruber*, *G. sacculifer*, *G. glutinata*) decrease in abundance. The deep and shallow-dwelling species and its ratio in core A7 reflect a major shift at ~9.4 cal. kyr B.P. (Figure 6). A similar shift can be also noticed in the distribution of several warm and cold species

in core A7 (Figure 4 and 5). The replacement of cold deep species by warm shallow species may suggest a sudden deepening of the DOT in the Okinawa Trough at that time. A shift can also be noticed at site E017 during ~8.2-9.4 cal. kyr B.P. (Figure 4, 5 and 6). The age difference of this shift between Cores A7 and E017 may be probably caused by the ash/turbidite deposit which leaded to a sediment gap in core E017.

3.4 Oxygen isotope records

The $\delta^{18}O$ record of *G. sacculifer* in core E017 is a little heavier than the $\delta^{18}O$ of *G. ruber* in core A7, consistent with a deeper water dwelling habit of *G. sacculifer* than that of *G. ruber* (Bé, 1977). Oxygen isotope records in both cores also show similar trends since the last deglaciation. The $\delta^{18}O$ values are high during the period of ~18-17 to 15.2 cal. kyr B.P., and become substantially lower by about 1.7‰ to the early Holocene (Figure 7). A heavy $\delta^{18}O$ period occurred at 15.3-16.8 cal. kyr B.P. corresponding to H1 of North Atlantic. A return to heavy $\delta^{18}O$ during 11.7-13.1 cal. kyr B.P occurred in both cores corresponding to the YD cold period. Two rapid decreases of $\delta^{18}O$ occurred at the beginning of B/A and at the end of YD, which correspond to the melt-water pulse (MWP)-1A and MWP-1B leading to exceedingly rapid rising in global sea-level (Fairbanks, 1989). Several large fluctuations during the Holocene are evident in core A7 at 6.2, 7.3 and 8.2 cal. kyr B.P., respectively, which is consistent with Mg/Ca based SST record. Note that $\delta^{18}O$ record of *G. ruber* show no apparent variation during the Holocene PME, although Mg/Ca SST (Sun et al., 2005) and warm/cold species ratio show an obvious decreasing in core A7 (Figure 7).

4. Discussion

4.1 Sedimentation rate changes since the last deglaciation

Sedimentation rate in the middle Okinawa Trough were higher during the last deglaciation than that during the Holocene (Figure 3). Similar trends are seen in two cores from the northern Okinawa Trough (Xu et al., 1999). For the middle Okinawa Trough, particulate matter from the Yangtze River is a major sediment source, and the down-slope transport of suspended particulate matter is a major mechanism of sediment transport (Chung and Hung, 2000). The sedimentation rate decreased at ~11.2 cal. kyr B.P. in the middle Okinawa Trough suggesting a sudden decrease in the amount of terrigenous matter entering into the trough, which was a closely linked to the rapid sea-level rise of the global ocean. During the last deglaciation, two prominent rapid sea-level rise events termed MWP-1A and MWP-1B were recorded in Barbados coral reefs (Fairbanks, 1989) and also in the EC/YS and SCS (Liu et al., 2004).

MWP-1A appears to have occurred at the end of Bølling Warm Transition at 14.3-14.1 cal. kyr B.P. when sea-level rose from -95 to -80 m (Liu et al., 2004). Accompanying this event is the intensification of summer East Asia Monsoon (EAM) which greatly increased the precipitation in the East Asia region (Wang et al., 1999). This was also recorded by the rapid reduction of $\delta^{18}O$

values in cores A7 and E017 (Figure 7). However, sedimentation rate in the middle Okinawa Trough show no apparent fluctuation corresponding to the MWP-1A, indicating that the enhanced sediment loading that was transported into the sea by Yangtze River due to intensified EAM rainfall may have counteracted by the retreat of river mouth during marine transgression.

MWP-1B occurred at the end of YD at 11.5-11.2 cal. kyr B.P. when sea-level rose from -58 to -43 m (Liu et al., 2004). Although the average rate of sea-level rise during MWP-1B was lower than that in MWP-1A, the area of submerged shelf on the ECS, however, was large after MWP-1B due to a low angle of slope of the inner and middle shelf of ECS. The estuary of the Yangtze River also retreated to a position very close to that of the modern river mouth after MWP-1B. Thus, suspended particles from the Yangtze River were mostly deposited on the inner shelf of the ECS, which caused a sudden decrease of terrigenous matter supplying to the Okinawa Trough by down-slope transport in spite of a dramatically enhanced Asia monsoon precipitation occurred at the end of YD (Morrill et al., 2003). This explains why sedimentation rate in the middle Okinawa Trough shows an abrupt decrease at ~11.2 cal. kyr B.P. (Figure 3).

Figure 3 also shows the regional distribution of sedimentation rate changes in the middle Okinawa Trough. Sedimentation rate in core A7 were higher than those in cores E017 and DGKS9603, both for the last deglaciation and the Holocene. This may indicate that one of the main paths for suspended particles from the Yangtze River to enter into the trough is near the core site of A7. However, the sedimentation rate in the northern Okinawa Trough (e.g. Cores DH82-4-14 and MD982195), was generally higher than that in the middle Okinawa Trough whether during the last deglaciation or the Holocene (Xu et al., 1999; Ijiri et al., 2005), suggesting that a large part of suspended matter from Yangtze and Yellow River were deposited in the northern Okinawa Trough.

4.2 Millennial-scale climate changes during the last deglaciation

Because some cool/cold water species (such as *G. bulloides*) are also affected by productivity, three major cold/cool water species *N. pachyderma* (dex.)+*G. inflata*+*G. quinqueloba* (not affected by productivity) were used to indicate the SST variations. The proxy show similar trends with Mg/Ca based SST and $\delta^{18}O$ during the last deglaciation (Figure 7). The abundances of planktonic foraminiferal species, Mg/Ca based SST, and isotope records from cores A7 and E017 exhibit millennial-scale fluctuations similar to climate in the high latitude North Atlantic region during the last deglaciation (Figure 7), confirming that SST fluctuations in the Okinawa Trough occurred nearly synchronously with H1, B/A and YD events in the high latitude North Atlantic.

The H1 event is characterized by a low abundance of *P. obliquiloculata*, which almost disappeared in the Okinawa Trough during this period (Figure 5). A similar event is seen in the northern area of the ECS (Xu et al., 1999; Ijiri et al., 2005). The duration of this cold event recorded by multiple proxies (e.g. *P. obliquiloculata*, Mg/Ca based SST and $\delta^{18}O$ of *G. ruber*) is well constrained to 15.3-16.8 cal. kyr B.P. in this subtropical marginal sea (Figure 7). This cold

event has a wide imprint in the East Asia region in records from loess, stalagmite and marine sediment (e.g., Porter and An, 1995; An, 2000; Wang et al; 2001; Yuan et al., 2004; Wang et al., 1999; Li et al., 2001; Ijiri et al., 2005), reflecting an increase in the intensity of the winter EAM. The timing is consistent with H1 (15.4-16.9 cal. kyr B.P.) recorded from high latitude North Atlantic region (Bond et al., 1993) and confirms a linkage with high-latitude Northern Hemisphere climate.

The last deglacial warming trend characterized by a rapid reduction of δ^{18}O values and a sudden increase of SST in the middle Okinawa Trough (Figure 7, Sun et al., 2005). During this deglacial transition, abundances of the cold *N. pachyderma* (dex.), *G. inflata* and *G. quinqueloba* dropped suddenly, while warm species such as *P. obliquiloculata*, *G. sacculifer* and *G. glutinata* increased (Figure 4 and 5). Thus, the warm/cold species ratio also shows an increase during this transition. This deglacial warming is coeval with δ^{18}O variations in the GISP2 ice core and stalagmite δ^{18}O variations from Hulu and Dongge caves in eastern and southern China (Stuiver and Grootes, 2000; Wang et al., 2001; Yuan et al., 2004). The timing of this warm period is constrained to 13.1-14.8 cal. kyr B.P. by the age model of core A7, which is consistent with B/A records from North Atlantic region (12.8-14.75 cal. kyr B.P.) within age uncertainty. As noted previously (Sun et al., 2005), a notable difference from the Greenland temperature record, which shows a peak warming at the early B/A (~14.5 cal. kyr B.P.) and then generally decreased, is that the Okinawa SST shows a steady warming that peaks late in the B/A. This difference is confirmed by the Okinawa Trough faunal changes, which show a steady increase in the warm/cold species ratio, peaking in the late B/A (~13.4 cal. kyr B.P.) (Figure 7). This late warming during the B/A is also documented from stalagmite records in southern and East China (Wang et al., 2001; Yuan et al., 2004) and marine sediment records from the northern ECS, the SCS, Santa Barbara Basin, and Cariaco Basin (Ijiri et al., 2005; Kiefer and Kienast, 2005; Lea et al., 2003), and suggests a tropical influence in the Okinawa Trough (Sun et al., 2005).

An obvious cold reversal during the period at 11.7-13.1 cal. kyr BP can be recognized from the abundance variations of planktonic foraminiferal species, SST and δ^{18}O record. Abundances of cold water species *N. pachyderma* (dex.), *G. inflata*, *G .quinqueloba* show an obvious increase during this period, while warm water species such as *P. obliquiloculata*, *G. ruber* and *G. glutinata* decreased (Figure 4 and 5). Mg/Ca based SST show a decrease of 1-2℃, and the δ^{18}O also show a slight increase during this time interval (figure 7). Deep-dwelling species also show a strong increase during this time span (figure 6), indicating a shallow of DOT, which may be caused by intensified winter EAM and weakened Kuroshio Current. This cold reversal is synchronous with the YD event (11.6-12.8 cal. kyr B.P.) recorded in the circum North Atlantic region (Grootes et al, 1993) within age uncertainty, which has a wide imprint in the Northern Hemisphere. The δ^{18}O and Mg/Ca based SST records in core A7 show large centennial fluctuations with an amplitude of ~0.7 ‰ for δ^{18}O and ~2℃ for SST in this time span, possibly indicates a superimposed tropical

influence. Such short-term climate fluctuations was also noticed by Zhou et al. (2001), who found a cold, dry YD climate was punctuated by a brief period of increased summer monsoon precipitation in the North China, and who interpret it as indicative of a global tele-connection involving moist air transportation patterns from the tropics to higher latitudes, varying with the El Niño/ Southern Oscillation (ENSO) and other tropical factors.

In summary, the last deglaciation pattern in the middle Okinawa Trough is characterized by millennial-scale climate changes: an intensified winter EAM during H1 at 15.3-16.8 cal. kyr B.P., a steady warming B/A at 13.1-14.8 cal. kyr B.P. and a cold YD at 11.7-13.1 cal. kyr B.P. This pattern is very similar to that in the high-latitude North Atlantic region, suggesting a strong climate tele-connection between the Okinawa Trough and high-latitude North Atlantic. The mechanism controlling the tele-connection between them is probably related to the meandering of the westerlies in the northern hemisphere (Wang and Oba, 1998; Ijiri et al., 2005) and variations of the winter EAM (Sun et al., 2005). However, superimposed centennial-scale surface hydrology variations that occurred during the B/A and YD, together with the steady B/A warming, may indicate a tropical influence that was previously attributed to variable influence of the warm Kuroshio Current (Sun et al., 2005). Some previous studies suggest that the Kuroshio Current was not present in the Okinawa Trough but shifted to a position east of the Ryukyu Islands (Ujiié and Ujiié, 1999) and re-entered the Okinawa Trough at ~7.3 cal. kyr B.P. (Jian et al., 2000). Our results showing relatively high values of warm water species *G. sacculifer* and *P. obliquiloculata*, indicative of the Kuroshio Current, after 15.3 cal. kyr B.P., suggest an influence of Kuroshio Current in the Okinawa Trough at least since this time, consistent with conclusions from studies of sediment from the northern part of ECS (Xu et al., 1999; Ijiri et al., 2005).

4.3 Early Holocene strengthening of the Kuroshio Current

The major shift in the distribution of deep/shallow-dwelling species at ~9.4 cal. kyr B.P (Figure 6) is also indicated by warm/cold speices ratio changes (Figure 7), suggesting a sudden deepening of DOT, which may be caused by a sudden strengthening of the Kuroshio Current in the Okinawa Trough. This sudden change in planktonic foraminifera in the Okinawa Trough is synchronous with a rapid sea-level rise (MWP-1C) at 9.5-9.2 kyr B.P. in the ECS, Yellow sea (YS) and South China Sea (SCS), rose from -36 to -16 m below modern sea-level (Liu et al., 2004). The sudden change in planktonic foraminifera and the rapid sea-level rise at ~9.4 cal. kyr B.P. suggest rapid paleoenvironmental change in the ECS. Additional evidence comes from the benthic foraminiferal record in core E017 (Figure 6). High abundances of infauna benthic foraminifera *Uvigerina* and *Bulimina* are usually good indicators of high organic matter flux, the sudden decrease of this proxy at ~8.2-9.4 cal. Kyr B. P. in core E017 may indicate a decrease of surface water paleoproductivity and organic matter flux which are also inferred by a sudden fall of benthic foraminifera accumulation rate (Li et al., 2005). This sudden decrease of paleoproductivity and organic matter flux may correspond to the rapid retreat of the estuary caused by rapid sea-level

rise of MWP-1C, which greatly reduced the terrigenous nutrients supply to the middle Okinawa Trough, and also due to the oligotrophic and low primary productivity characters of the Kuroshio water (Gong et al., 2000).

4.4 Holocene variability of marine environment

The Holocene Okinawa Trough is also characterized by a series of millennial-scale environment changes, among which the PME is the most remarkable event (Li et al., 1997; Jian et al., 2000, Ujiié et al., 2003), marked by a slight drop of temperature in both cores A7 and E017. Other cold events at about 1.7, 6.2, 7.3 and 8.2 cal. kyr B.P. can be also inferred from the relative abundances of cold and warm species variations in the high-resolution core A7 (Figure 4, 5 and 7), as well as Mg/Ca based SST, which further indicates two cold events at around 9.6 and 10.6 cal. kyr BP (sun et al., 2005). This Holocene variability has also been suggested by SST and $\delta^{18}O$ differences between core 255 from the southern Okinawa Trough and core B-3GC in the northern ECS (Jian et al., 2000). Our results further confirm that the Holocene environment in the Okinawa Trough experienced millennial-scale changes, which may reflect the fluctuations of Kuroshio Current, with a weakened Kuroshio Current during these cold events (Jian et al., 2000; Sun et al., 2005). Like many SST records from the SCS (Kiefer and Kienast, 2005 and references therein), a general Holocene warming trend can also be inferred from the relative abundance of warm and cold species in both cores A7 and E017, consistent with the Mg/Ca based SST of core A7 (Sun et al., 2005). This warming trend may be related to a tropical response to insolation forcing (Liu et al., 2003), communicated to the Okinawa Trough via the Kuroshio Current.

5.   Conclusions

Paleoevrionmental changes in the middle Okinawa Trough since the last deglaciation were deduced from two well AMS[14]C dated sediment records. Based on planktonic foraminiferal analyses and oxygen isotope analyses, we drew the following conclusions on millennial-scale climate and ocean variability for the last ~17-18 cal. kyr B.P.

1.   The sedimentation rate in the middle Okinawa trough was higher during the last deglaciation than in the Holocene. A sudden decrease of sedimentation rate occurred at ~11.2 kyr B.P., which may have been caused by rapid rise of sea-level after the YD (MWP-1B) and consequently a retreat of estuary and a large submerged continental shelf on the East China Sea (ECS). The sedimentation rate in the northern Okinawa Tough has been generally more rapid than that in the middle Okinawa Trough over the past 17-18 cal. kyr B.P., suggesting that a large part of the suspended sediment from the Yangtze and Yellow Rivers was deposited in the northern Okinawa Trough.

2.   The general trend of the last deglaciation in the middle Okinawa Trough is very similar to high-latitude North Atlantic. Results from abundance of planktonic foraminiferal species, Mg/Ca based SST, and isotope records all suggest a cold period contemporaneous with H1 at

15.3-16.8 cal. kyr B.P., a steady warming during the B/A at 13.1-14.8 cal. kyr B.P. and a cold YD at 11.7-13.1 cal. kyr B.P. Evidence presented here confirms a strong climate teleconnection between the Okinawa Trough and high-latitude North Atlantic during the deglaciation, consistent with an East Asian Monsoon link (Sun et al., 2005) and/or a linkage through meandering of the high latitude westerlies (Wang and Oba, 1998; Ijiri et al., 2005).

3. Centennial-scale Mg/Ca based SST variations superimposed on the last deglacial oscillations, may suggest a tropical influence on the Okinawa Trough during this period. Our results indicate that the Kuroshio Current, though weakened, flowed into the ECS from the east side of Taiwan since at least 15.3 cal. kyr B.P.

4. Planktonic foraminiferal assemblage show a marked change at about 9.4 kyr B.P. Shallow-dwelling species increase in abundance while deep-dwelling species decrease, suggesting deepening of the DOT in the middle Okinawa Trough. This may indicate a sudden strengthening of the Kuroshio Current in the Okinawa Trough, synchronous with a rapid sea-level rise at 9.5-9.2 kyr B.P. in the ECS, Yellow sea (YS) and South China Sea (SCS).

5. A series of millennial-scale environment changes, that occurred at about 1.7, 2.3-4.6, 6.2, 7.3, 8.2, 9.6, 10.6 cal. kyr BP, were recorded in core A7. These cold events, superimposed on the Holocene warming trend, may have been associated with the weakened Kuroshio Current in the Okinawa Trough. The Holocene warming trend in the Okinawa Trough may involve a tropical response to insolation forcing.

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Table 1. AMS[14]C age data for core E017[1]

Sample no.	Depth (cm)	Dating material	AMS[14]C age, years B.P.	Calendar years B.P.	2σ Error Bars, years	Dated Lab.
E017-1	14-24	*N. dutertrei*	3170±60	2680	2430, 2757	b
E017-2	98-100	*N. dutertrei*	8760±120	9040	8723, 9398	b
E017-3	152-158	*N. dutertrei*	10750±85	11560	11253, 11906	a
E017-4	172-176	*N. dutertrei*	11600±180	12870	12562, 13206	b
E017-5	228-232	*N. dutertrei*	13560±140	15170	14706, 15682	b
E017-6	246-248	*N. dutertrei*	15250±70	17580	17066, 17926	a
E017-7	280-286	*N. dutertrei*	14950±75	17030	16578, 17453	a

[1]All ages were estimated from calibration curve MARINE04 (Hughen et al., 2004) with a 700-year reservoir age.

[a]National Ocean Sciences Accelerator Mass Spectrometry (AMS) Facility, the Woods Hole Oceanographic Institution, USA.

[b]Ministry of Education Key Laboratory of Heavy Ion Physics, Peking University, China.

Figure caption

Figure 1. Locations of cores A7 and E017 and other coring sites in the middle and southern Okinawa Trough. Shade arrows indicate the Kuroshio Current and its branches, and solid lines are the isobaths.

Figure 2. Age model construction of core E017 with 5 additional comparative age control points (hollow triangle) obtained by lithological and biostratigraphic correlation with core A7, which has been detailed AMS[14]C dated. 3 are obtained by percentage abundance correlations of *P. obliquiloculata*, *G. bulloides* and *N. pachyderma* (dex.), and 2 are obtained by a turbidite/ash layer correlation between core E017 and core A7. Lithology and the positions of AMS[14]C dating (solid

triangle) of cores A7 and E017 are also shown.

Figure 3. Rates of sedimentation in three sediment cores taken from the Okinawa Trough. Solid circles signify AMS[14]C ages with error bars. Triangles are estimated ages based on lithologic and biostratigraphic correlation. The data sets indicate that the rates of sedimentation decreased after about 11.2 cal. kyr B.P.

Figure 4. Variations of percentage abundance of cold water foraminiferal species and warm/cold species ratio in core A7 (A) and core E017 (B) during the last 17-18 cal. Kyr B.P. Solid line represents a sudden decreasing of cold water species at ~9.4 cal. kyr B.P. Shade areas indicate the *Plleniatina* minimum event (PME).

Figure 5. Variations of Percentage abundance of warm water foraminiferal species in core A7 (A) and core E017 (B) during the last 17-18 cal. Kyr B.P. Shade areas indicate the *Plleniatina* minimum event (PME).

Figure 6. Abundance profiles of deep and shallow-dwelling species and deep/shallow species ratio in cores A7 and E017. Also shown is the percentage abundance of *Uvigerina+Bulimina* group from benthic foraminifera in core E017. Solid line indicates a sudden change of these proxies at ~9.4 cal. kyr B.P.

Figure 7. Time plot of δ^{18}O, warm water species and warm/cold species ratio in cores A7 and E017 and Mg/Ca-based SST (Sun et al., 2005) in core A7. Shade areas indicate millennial-scale climate change events since the last deglaciation. Dashed lines represent small cold peaks during the Holocene. PME, *Plleniatina* minimum event; YD, Younger Dryas event; B/A, Bølling and Allerød warm phase; H1, Heinrich event 1.

Appendix table.　　Repeatedly analyzed Planktonic foraminifera data on 26 horizons of core A7