

Millennial-Scale Planktic Foraminifer Faunal Variability in the East China Sea during the Past 40000 Years (IMAGES MD012404 from the Okinawa Trough)

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ABSTRACT

High resolution planktic foraminifer fauna assemblage data are used to reconstruct the millennial-scale sea surface temperature (SST) variability of the past 40000 years at an IMAGES core site (MD012404) in the Okinawa Trough in the East China Sea (ECS). The fauna assemblages in core MD012404 are dominated by five species – *Globigerinoides ruber*, *Globigerina bulloides*, *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, and *Globigerinita glutinata*, which account for > 70% in relative abundance. Our Q-mode factor analysis decomposed the fauna abundance data into three factors, which indicate cold water mass, warm water mass, and possibly coastal water flow with low salinity in the ECS. The MD012404 fauna data show abrupt changes at ~16 kya, suggesting a return to a warmer climate or warm water intrusion of the Kuroshio into the Okinawa Trough since the Last Glacial Maximum (LGM). SST estimates based on the fauna assemblages of planktic foraminifers indicate a LGM cooling of 1 - 2°C. A maximum cooling by 3 - 4°C is observed in episodic, millennial-scale events in the glacial stages of the record. The SST record displays variability that closely tracks the structure of oxygen isotopes of stalagmites from Hulu Cave and ice cores from GISP 2 Dansgaard/Oeschger cycles and Heinrich events. Low salinity in the ECS is inferred based on MD012404 fauna SST and planktic foraminifer oxygen isotope records for the cold millennial-scale intervals, pointing to the Intertropical Convergence Zone (ITCZ) and/or East Asian monsoon as important factors driving SST and salinity in the subtropical western Pacific, both on orbital and suborbital time scales.

Key words: Planktic foraminifer, Sea surface temperature, ITCZ, East China Sea, Okinawa Trough, IMAGES

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1. INTRODUCTION

The East China Sea (ECS) is one of the marginal seas of the western Pacific, located between the Japan Sea and the South China Sea and connected to Asia with wide continental shelves. The Okinawa Trough is a back-arc spreading basin in the southeastern part of the ECS. The surface hydrography in the ECS near the Okinawa Trough is governed by the Kuroshio, a main western boundary current in the northwestern Pacific. The Kuroshio waters are warm

(> 20°C) and have relatively high salinities (≥ 34 psu), flowing along the western edge of North Pacific subtropical mode water (NPSTMW). The Kuroshio is responsible for great heat and moisture transport from the tropics to the middle latitudes (Hsueh 2000; Ichikawa and Chaen 2000). The mean seasonal range of surface heat transports in the Okinawa Trough is $\sim 300 \text{ E m}^{-2}$ (Qiu et al. 2004).

Playing an important role in the global climate system, the Kuroshio also has a strong impact on regional surface hydrography in the western Pacific near East Asia. Under the control of the complicated bathymetry of the western Pa-

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cific basins, the Kuroshio enters the ECS along the eastern side of Taiwan and intrudes into the Okinawa Trough along the ECS's continental shelves (Fig. 1). The seasonal SST and salinity of the ECS near the Okinawa Trough are also controlled by East Asian monsoons. The observed mean annual SST is $\sim 24.7^{\circ}\text{C}$, with a seasonal range between $\sim 28.6^{\circ}\text{C}$ (July) and $\sim 21.8^{\circ}\text{C}$ (January). Mean annual sea surface salinity is ~ 34.4 psu, with a summer low of ~ 34.1 psu and a winter high of ~ 34.7 psu [National Oceanic and Atmospheric Administration (NOAA) 1994]. The seasonal salinity variability in the ECS is largely influenced by fresh water input from the Yangtze River (Changjiang). During the summer, strong summer monsoons (southwesterly) and the relatively northward Intertropical Convergence Zone (ITCZ) bring high precipitation into southern China, the drainage area of the Yangtze River, which in turn leads to a great volume of fresh water discharge that reduces surface salinity in the ECS. The relatively low summer salinity observed in the ECS indicates dominant monsoon and/or ITCZ effects relative to the intrusion process of the Kuroshio, which is transporting more saline water from the Pacific in the summer.

Previous work using planktic foraminifer fauna-based hydrographic records from the Okinawa Trough has suggested that the Kuroshio intrusion flow was blocked by the land bridge of the Ryukyu Arc during lower sea level glacial conditions (Ujiié et al. 1991; Ahagon et al. 1993; Ujiié and Ujiié 1999). It has been assumed that the Kuroshio did not penetrate into the Okinawa Trough during the glacial period from 16 to 45 kya (Li et al. 2001). The weak strength of the North Equator Current where the Kuroshio originates, with an ENSO-like climatic condition in the equatorial Pacific, may have led to the eastward migration of the Kuroshio during the *Pulleniatina* Minimum Event (PME) ~ 3.5 kya (Ujiié et al. 2003). This interpretation is consistent with modern hydrographic observations that the Kuroshio is weakened during El Niño years and strengthened in La Niña years (Kim et al. 2004). Other ECS sediment core studies (Jian et al. 1996, 2000b; Li et al. 1997) also have proposed the same scenario – that the Kuroshio was weak and/or shifted toward the Pacific during the PME in ~ 2 to 5 kya of the late Holocene. But a reconstructed Mg/Ca SST record had shown that the SST did not have a declining trend during this period (Lin et al. 2006), and the author concluded that PME might have resulted from a decrease or migrating of the Kuroshio. All evidence from previous works has suggested short-term, millennial-scale variability in surface hydrography in the ECS during the late Quaternary.

Large surface ocean cooling has been inferred in the ECS during the Last Glacial Maximum (LGM) and the Younger Dryas (YD) using transfer function-type planktic foraminifer SST estimates and evidence of low abundances of the Kuroshio indicator species *Pulleniatina obliquiloculata* (Li et al. 1997; Liu et al. 1999; Li et al. 2001). These

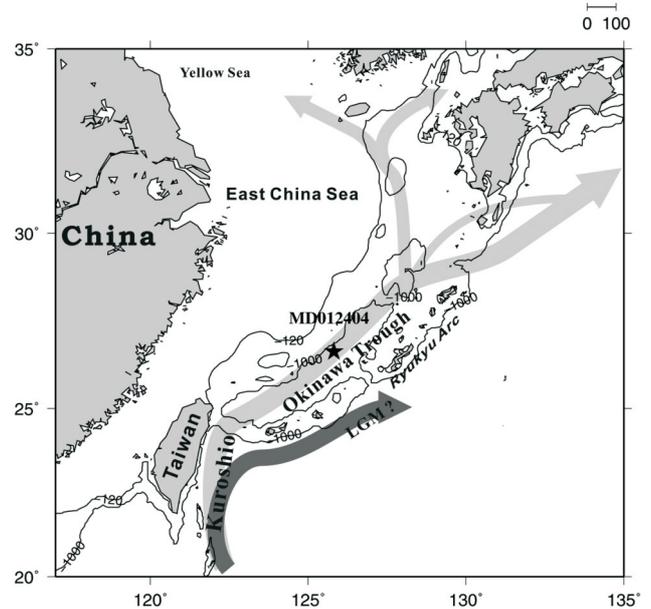


Fig. 1. Physiographic map showing the location of core MD012404. The modern flowing path of the Kuroshio is indicated by a gray line and the possible change of the Kuroshio main stream in LGM is shown as a dark line with a question mark.

previous studies also reported a similar magnitude of cooling in surface ECS waters during the past four Heinrich events (H1 to H4) that were observed in the high-latitude North Atlantic and globally (Bond et al. 1992; Hemming 2004). Large-scale shifting or absence of the Kuroshio in the Okinawa Trough in response to intensified East Asian winter monsoons and/or coastal cold water from the north was called upon to explain large SST or fauna variability. A later study using planktic foraminifer fauna and pollen assemblages suggested, however, that the Kuroshio existed in the Okinawa Trough throughout the last glacial stage (Kawahata and Ohshima 2004). More recently, a short 20-kyr long record from the Okinawa Trough using planktic oxygen isotope and Mg/Ca SST has indicated a warming trend with increased salinity since the last deglaciation in the ECS (Sun et al. 2005). This glacial to interglacial transition of surface hydrography echoes the increased strength of the East Asian summer monsoon since the early Holocene that has been proposed by most previous monsoon studies. Superimposed on the long-term trend, this study suggests that the millennial-scale variability in the ECS is characterized by a series of warm/saline, and cold/fresh conditions, which need other mechanisms to account for the millennial-scale variability. Despite possibly complicated mechanisms, all of these cases indicate a need for long-term, and high-resolution records for better reconstruction of SST and salinity in order to identify all possible factors and linkages governing climate variability in the ECS.

In the current study, high-resolution planktic foraminifer fauna abundance data and SST estimates were generated

from core MD9012404, which was collected in the middle part of the Okinawa Trough from a WEPAMA cruise of the IMAGES (International Marine Global Changes Study) program in 2001 (Bassinot et al. 2002). Specific objectives of this study are to: (1) document the high-resolution, millennial-scale variations of planktic foraminifer fauna assemblages of the past 40000 years in core MD012404; (2) estimate SST variations based on the planktic foraminifer fauna record using the Revised Analog Method (RAM) (Waelbroeck et al. 1998); (3) estimate the SST changes in the ECS; and (4) identify the linkage between the ECS SST record and a stalagmite monsoon record from Hulu Cave (Wang et al. 2001), and a GISP ice core record from the high latitudes of the Northern Hemisphere (Grootes and Stuiver 1997).

2. MATERIALS AND METHODS

2.1 Core Descriptions and Age Models

The IMAGES core MD012404 used in this study was taken at 26°38.84'N, 125°48.75'E in the middle part of the Okinawa Trough at a water depth of 1397 m, which is well above the carbonate lysocline (~3000 m) of the western Pacific (Thunell et al. 1992) (Fig. 1). The total length of core MD012404 is 43.67 m. The sediment compositions of the

core are silty clays dominated by nannofossil ooze with diatoms and foraminifers. The color of the sediment core changes from grayish olive green to olive gray with dark organic-rich layers and spots (Bassinot et al. 2002). No visible layers of volcanic ash are found in the sediments; pyrites or volcanic glasses are found at some intervals of the core. The sediments were sliced into 1-cm thick samples on board and were kept in a refrigerator under 4°C before processing. Sub-samples of approximately 10 g were taken from the slice samples at 5-cm depth intervals for the purpose of this study in order to conduct planktic foraminifer assemblage analysis. All laboratory procedures were done in the Laboratory of Earth, Environment and Climate Variability, Institute of Applied Geosciences at the National Taiwan Ocean University.

The age model of core MD012404 was established using planktic foraminifer AMS ¹⁴C dating. We added 14 new AMS ¹⁴C datings to those presented in Chang et al. (2005) in the age control of the record of the past 40000 years (Table 1). The AMS ¹⁴C measurements were done by taking ~20 mg of planktic foraminifers *G. ruber* and *G. sacculifer* (> 250 μm) shells and dating them at the Micro Analysis Laboratory's Tandem Accelerator (MALT) at The University of Tokyo. All AMS ¹⁴C ages were adjusted for a mean Pacific reservoir age of 400 years. All ages younger than 21000 years BP

Table 1. AMS ¹⁴C age control points used to age the model of core MD012404. Reservoir age of 400 years was subtracted from the ¹⁴C ages before calibration. A CALIB 5 program and Bard's (2004) equation were used in the calibration.

Depth (cm)	AMS ¹⁴ C Age	Error ^a	Calendar Age (year)	Species
14.5	1040	± 70	749	<i>G.sacculifer</i>
104.5	2350	± 30	2150	<i>G.sacculifer</i> + <i>G.ruber</i>
254.5	4500	± 110	4875	<i>G.sacculifer</i>
349.5	6450	± 30	7093	<i>G.sacculifer</i> + <i>G.ruber</i>
494.5	9730	± 120	10818	<i>G.sacculifer</i>
589.5	10820	± 190	12366	<i>G.sacculifer</i>
624.5	11370	± 40	13093	<i>G.sacculifer</i> + <i>G.ruber</i>
744.5	12680	± 130	14686	<i>G.sacculifer</i>
854.5	13950	± 90	16299	<i>G.sacculifer</i>
904.5	14560	± 45	17058	<i>G.sacculifer</i> + <i>G.ruber</i>
1019.5	15810	± 160	18822	<i>G.sacculifer</i>
1194.5	19520	± 230	22975	<i>G.sacculifer</i>
1379.5	21360	± 70	25307	<i>G.sacculifer</i> + <i>G.ruber</i>
1454.5	23230	± 270	26757	<i>G.sacculifer</i>
1539.5	24450	± 490	28122	<i>G.sacculifer</i>
1719.5	27970	± 200	32019	<i>G.sacculifer</i> + <i>G.ruber</i>
1814.5	30200	± 230	34456	<i>G.sacculifer</i> + <i>G.ruber</i>
2074.5	32490	± 1110	36932	<i>G.sacculifer</i> + <i>G.ruber</i>
2174.5	34010	± 280	38561	<i>G.sacculifer</i> + <i>G.ruber</i>

a. Error is given in 1σ

were calibrated into calendar years by using CALIB program 5.0 (Stuiver et al. 2005), and those older than 21000 years BP were calibrated using the equation found in Bard et al. (2004). With this age model, the mean sedimentation rate was estimated to be approximately 50 cm kyr^{-1} in the record of MD012404 during the past 40000 years (Fig. 2h), and it is able to resolve millennial-scale variability in the past ECS climate.

Oxygen isotopes of the planktic foraminifer *G. ruber* (white) sensu stricto (s.s.) were also measured for core MD012404 in order to resolve the hydrographic history of the ECS during the past 40000 years. The oxygen isotope analyses were done using a Micromass IsoPrime isotope ratio mass spectrometer housed in the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST) at Tsukuba, Japan. The NBS-19 was used as the carbonate standard for calibrating the *G. ruber* shell samples to the PeeDee Belemnite (PDB).

Volcano glass abundance layers were observed at core depths of 354 and 1559 cm. These layers are dated as 7.3 and 28.5 kya, and coincide with major eruption events re-

corded in the northern volcanoes of Kikai and Aira on Kyushu Island, Japan (Machida and Arai 1976; Machida and Arai 1978; Machida 1999; Machida 2002).

2.2 Planktic Foraminifer Fauna Assemblages

High-resolution planktic foraminifer faunal abundance data were generated from core MD012404 in this study. Samples from every 5-cm interval from the top 15 m and from every 10-cm interval from 15- to 21-m depths, a total of 366 samples, were used for the fauna analyses. All samples were freeze-dried and weighed, and then washed through a $104\text{-}\mu\text{m}$ sieve under a weak spray of water. After drying the washed samples in a 50°C oven overnight, the samples were again sieved through a $> 149 \mu\text{m}$ size fraction and split into sub-samples which contained > 300 whole specimens for identifying and counting under a microscope. The taxonomy of planktic foraminifers adopted in this study followed the scheme used in compiling a new western Pacific coretop database (Chen et al. 2005), in which *Globorotalia menardii* and *Globorotalia tumida* were combined into one species,

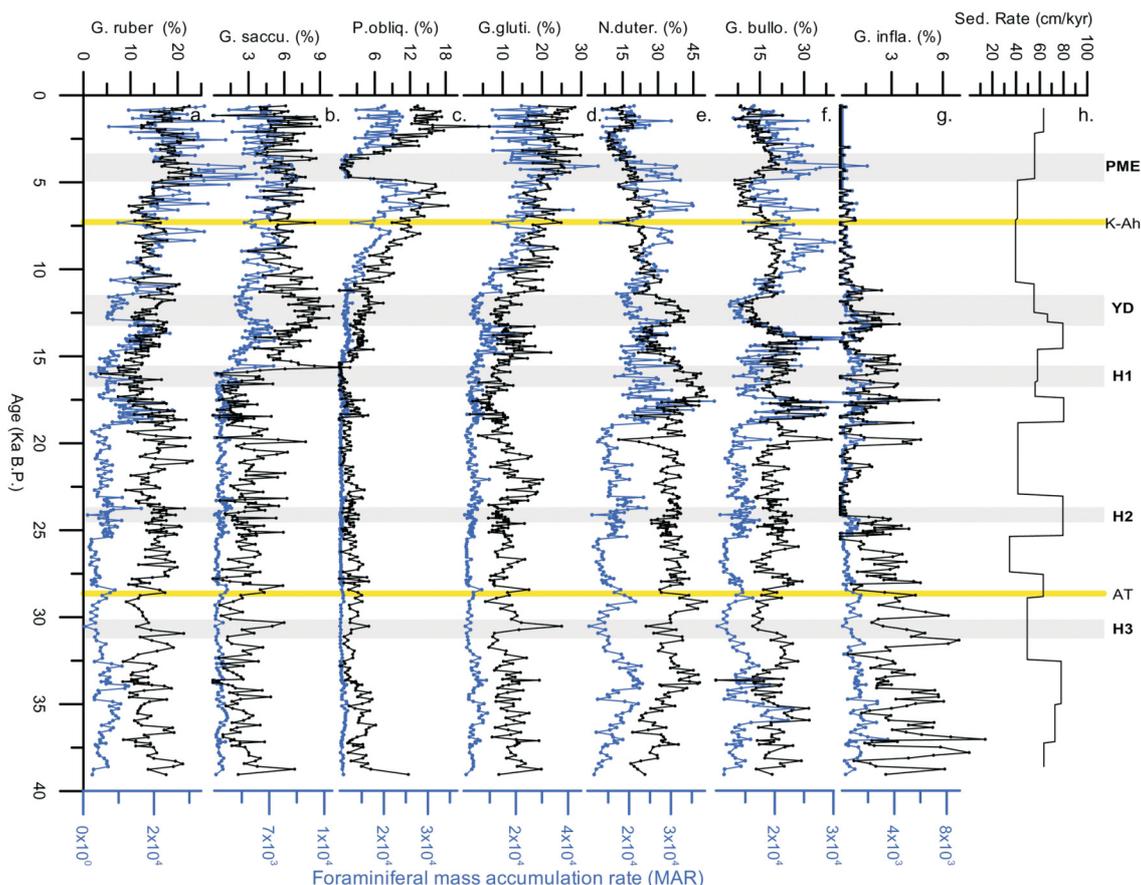


Fig. 2. Downcore variations in planktonic foraminiferal assemblages and the mass accumulation rate (MAR) are represented by a gray line. (a) *G. ruber*, (b) *G. sacculifer*, (c) *P. obliquiloculata*, (d) *G. glutinata*, (e) *N. duterrei*, (f) *G. bulloides*, (g) *G. inflata*, (h) sedimentation rate. Triangles indicate the calibrated ^{14}C age used to reconstruct the age model in this study. Shadow areas mark the Heinrich events with a number and the Younger Dryas is denoted by YD in the above. Two volcanic eruption events at 7.3 and 28.5 ka BP are marked with a gray bar, which denotes K-Ah and AT, respectively.

G. menardii, and *Neogloboquadrina dutertrei* and *Neogloboquadrina pachiderma* (dextral) also were lumped into one unit, *N. dutertrei*. All fauna counting data are presented in relative abundances of species and also in absolute abundances (the total number of foraminifer shells per gram of sediment). A Q-mode factor analysis was applied by using the CABFAC program (Imbrie and Kipp 1971; Klován and Imbrie 1971) to reduce the fauna abundance data into a few independent factors for interpreting water mass or hydrographic variations in the downcore records.

We calculated the mass accumulation rate [MAR, (#n cm⁻²) kyr⁻¹] of foraminifers by using a procedure suggested in (Sykes and Ramsay 1995). On-board gamma ray density data were used as wet bulk density (WBD) (Bassinot et al. 2002). Porosity data were calculated following Simmons (1990):

$$\text{MAR} = F \times [\text{WBD} - (P \times \text{WD})] \times \text{SR} \quad (1)$$

where F is the total number of foraminifers (#n g⁻¹), WBD is wet bulk density (g cm⁻³), P is porosity (P = 0.72 - 0.045Z, Z = core depth in km) (Simmons 1990), and WD is the density of seawater (1.03 g cm⁻³) (Beicher 2000).

2.3 RAM SST Estimates

The Revised Analog Method (RAM) (Waelbroeck et al. 1998) was used in this study for estimating MD012404 SST variation during the past 40 kya. The RAM was proposed to improve the accuracy and precision of SST estimations based on planktic foraminifer fossil faunas. The RAM uses a dissimilarity coefficient (squared chord distance) to measure the dissimilarity between the fauna abundance data of coretop and downcore samples. Higher values of the squared chord distance indicate less similar samples. The squared chord distance also has the effect of amplifying the signals of less dominant species abundances. This method was considered valid with a precision of $\leq 1^\circ\text{C}$ in testing against a western Pacific coretop database (Chen et al. 2005). We used a threshold value of the dissimilarity coefficient of 0.6 with the RAM and reported summer, winter, and annual average SSTs from the fauna record of core MD012404.

3. RESULTS AND DISCUSSION

At the MD012404 core site of the Okinawa Trough in the ECS, fauna analyses of planktic foraminifers reveal that out of a total 27 identified species, there are seven dominant species with abundances $\geq 3\%$ (Table 2). The most abundant species, *N. dutertrei*, constitutes $\sim 50\%$ at its maximum and also a gradually decreasing pattern from 40 kya to the Holocene (Fig. 2e). The abundances of *N. dutertrei* are high in glacial stages MIS (Marine Isotope Stage) 2 to MIS 3, and appear to be an indicator of cold water mass in the ECS

(Fig. 2e). *Globigerina bulloides* is the second dominant species, reaching $\sim 40\%$ at its maximum, and relatively high abundances but more high-frequency oscillations during glacial stages (Fig. 2f). In the surface sediments, *G. bulloides* abundances are relatively higher on ECS continental shelves, indicating cold coastal waters (Xu and Oda 1999). The abundances of the tropical and sub-tropical species *G. ruber* (15% on average) (Fig. 2a), *G. sacculifer* (4% on average) (Fig. 2b), *Globigerinita glutinata* (14% on average) (Fig. 2d), and *P. obliquiloculata* (4% on average) (Fig. 2c) all display gradually increasing trends from the LGM to the Holocene, suggesting a return back to warm water mass conditions in the ECS after the glacial periods or a reentering of the Kuroshio into the Okinawa Trough from the Pacific. Previous studies suggest that these warm water species are associated with the main path of the Kuroshio (Oda and Takemoto 1992; Ujiie and Ujiie 1999; Xu and Oda 1999). A PME-type event with minimum *P. obliquiloculata* abundances is also observed in the MD012404 record of ~ 3 to 5 kya (Ujiie et al. 1991; Li et al. 1997; Ujiie and Ujiie 1999; Ujiie et al. 2003) (Fig. 2c).

Two deep-dwelling species, *Globolotalia inflata* (Fig. 2g) and *Globolotalia truncatulinoides* (left + right coiling morphotypes) (Fig. 3), display temporal variations that might be linked to deep thermoclines and/or thick mode water thermostads in the ECS. *G. inflata* is an indicator for transitional and subpolar water, preferring to live at the bottom of thermocline depths (Bé 1977; Hemleben et al. 1989). High abundances of *G. inflata* indicate conditions of weakly stratified water columns with strong coastal upwelling, e.g., the Peru Current in the southeastern Pacific (Feldberg and Mix 2002). In MD012404, *G. inflata* appears in relatively high abundance in the glacial stages but increases abruptly in short episodes of the record. *G. truncatulinoides* is also indicative of deep mixing conditions in the upper layer of surface oceans as well as the thickness of the NPSTMW thermostads (Jian et al. 2000a). The occurrence of *G. truncatulinoides* in glacial stages (Fig. 3a) is therefore used to infer a strongly mixing, more weakly stratified layer of upper ocean conditions in the ECS during the glacial periods.

The MAR of all planktic foraminifers reveals a gradually increasing trend from 35 kya to the Holocene, and an abruptly increasing one since 16 kya (Fig. 3d). We also found a similar trend of gradual increase in the MAR of warm planktic foraminifer species that include *G. ruber*, *G. glutinata*, and *P. obliquiloculata* since ~ 16 kya (Fig 3b). This trend has been assumed to indicate the intrusion of the Kuroshio into the Okinawa Trough (Ujiie and Ujiie 1999; Ujiie et al. 2003; Kao et al. 2005, 2006). The change of the foraminifer MARs coincides with the variations of carbonate contents in MD012404 (Fig. 3d), suggesting that the carbonate contents are driven by foraminifer productivity and/or carbonate preservation in the Okinawa

Table 2. Statistic of 27 planktic foraminifer species abundance data from 364 downcore samples of core MD012404.

Foraminifera species	Average (%)	St. Dev. (%)	Minimum (%)	Maximum (%)
<i>Orbulina universa</i>	0.87	0.69	0.00	4.24
<i>Globigerinoides conglobatus</i>	0.34	0.47	0.00	2.30
<i>Globigerinoides ruber</i>	14.85	3.47	3.68	24.94
<i>Globoturborotalita tenellus</i>	1.38	0.81	0.00	4.67
<i>Globigerinoides sacculifer</i>	4.34	2.38	0.00	11.52
<i>Sphaeroidinella dehiscens</i>	0.04	0.13	0.00	1.08
<i>Globigerinella aequilateralis</i>	1.12	0.68	0.00	3.74
<i>Globigerinella calida</i>	3.35	1.76	0.00	13.97
<i>Globigerina bulloides</i>	18.68	5.64	0.00	39.22
<i>Globigerina falconensis</i>	0.73	0.75	0.00	4.10
<i>Beela digitata</i>	0.10	0.19	0.00	1.03
<i>Globoturborotalita rubescens</i>	1.40	0.83	0.00	4.59
<i>Turborotalita humilis</i>	0.01	0.07	0.00	0.61
<i>Globigerina quinqueloba</i>	0.64	0.89	0.00	6.67
<i>Neogloboquadrina pachyderma</i> (L)	0.10	0.23	0.00	1.22
<i>Neogloboquadrina dutertrei</i> *	30.54	9.87	8.78	50.66
<i>Globoquadrina conglomerata</i>	0.50	0.72	0.00	3.77
<i>Pulleniatina obliquiloculata</i>	4.54	4.67	0.00	25.39
<i>Globotalia inflata</i>	1.28	1.45	0.00	6.95
<i>Globotalia truncatulinoides</i> (L)	0.02	0.11	0.00	1.39
<i>Globotalia truncatulinoides</i> (R)	0.43	0.47	0.00	2.60
<i>Globotalia crassaformis</i>	0.09	0.20	0.00	1.50
<i>Globotalia hirsuta</i>	0.07	0.18	0.00	1.48
<i>Globotalia scitula</i>	0.33	0.44	0.00	2.34
<i>Globotalia menardii</i>	0.65	0.64	0.00	2.93
<i>Globotalia tumida</i>	0.01	0.06	0.00	0.90
<i>Globigerinita glutinata</i>	13.59	5.87	1.68	30.19

* *N. dutertrei* includes *N. dutertrei* and *N. pachyderma* (R).

Trough. Our foraminifer fragmentation index [WPF: whole planktic foraminifer / (WPF + Fragments)] indicates good preservation in the glacial and more dissolution in the interglacial periods in the MD012404 record (Fig. 3c), ruling out the possibility that the carbonate contents are driven by preservation changes. The glacial low carbonate contents in MD012404 appear to reflect the dilution effect of increased terrestrial, relative to carbonate, sediments in the Okinawa Trough during low sea level conditions. The dilution effects of volcanic glasses are also clearly observed in the relatively low carbonate content and MAR of the record at 7.3 and 28.5 kya that are labeled K-Ah and AT, respectively (Fig. 3d).

Our Q-mode factor analysis of the relative abundance data of the 27 planktic foraminifer species assemblage in core MD012404 (Table 3) indicates that three factors account for > 97% of the total variance of the data (Table 3).

The first factor explains 58% of the total variance and is entirely dominated by *N. dutertrei* (*N. dutertrei* + *N. pachyderma* dex.). Factor 1 loadings show high abundances in glacial stages but exhibit a decreasing trend since ~16 kya (Fig. 4a). Higher values of the factor 1 loadings are found in the Heinrich, YD, and PME intervals (Fig. 4a). Factor 2 explains 36% of the total variance and is correlated with the abundances of warm water mass assemblages *G. ruber*, *G. glutinata*, and *P. obliquiloculata* (Table 3). Factor 2 loadings are relatively low in glacial stages but increase gradually from ~16 kya (Fig. 4b). Low factor 2 loadings are observed in Heinrich, YD, and PME events. Factor 3 only explains 4% of the total variances and is dominated by one species, *G. bulloides* (Table 3). This species generally indicates nutrient-rich upwelling conditions (Bé 1977), and is abundant in the continental shelf of the ECS and the edge of the Kuroshio (Ujiié and Ujiié 1999; Xu and Oda 1999). The variations of

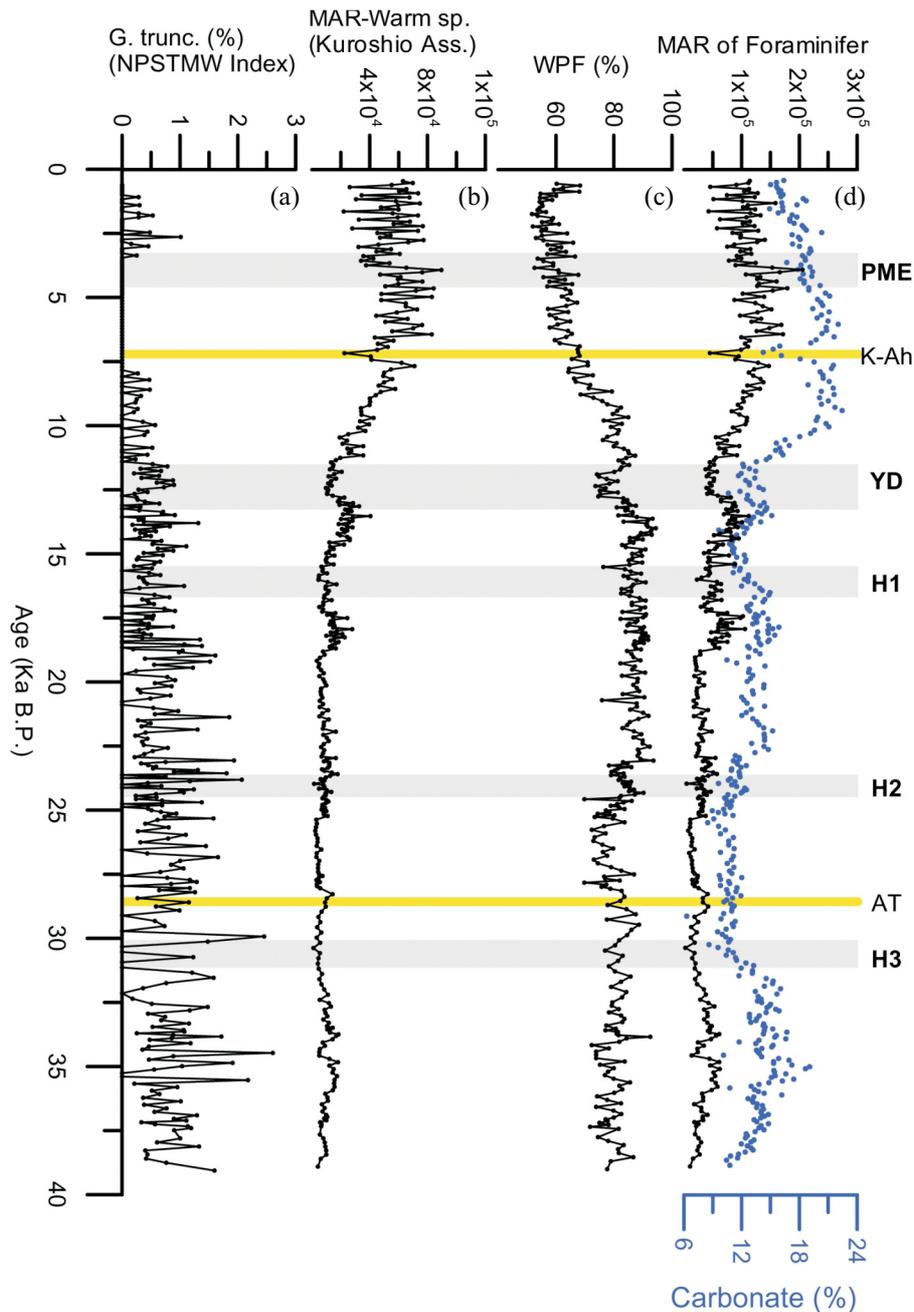


Fig. 3. (a) Percentage data of *G. truncatulinoides* were compiled with dextral and sinistral individuals which can be seen in the NPSTMW index in the North Pacific. (b) MAR data of warm species that combined with *G. ruber*, *G. glutinata*, and *P. obliquiloculata* to give the Kuroshio index in this study. (c) The preservation index which reveals the dissolution effect in this region. (d) MAR data that was calculated with all foraminiferal species and can serve as an index of carbonate productivity; gray dots represent the measured carbonate data.

factor 3 loadings display high-frequency oscillations without obvious correlations with millennial-scale climatic events (Fig. 4c). We speculate that this third factor could be an indicator of local mixing processes associated with high nutrient levels and/or riverine input between the zone of the continental shelf and the edge of the Kuroshio in the ECS (Ijiri et al. 2005).

A high-resolution MD012404 SST record was produced by applying a RAM based on the planktic foraminifer fauna

abundance data (Fig. 5b). Summer, winter, and annual average SSTs were reconstructed to reveal the sea surface water condition changes in the Okinawa Trough of the ECS. The dissimilarity coefficients between coretop and downcore samples range from 0.04 to 0.38, with a mean value of 0.15, indicating that good analogues were used to calculate the RAM SSTs (Fig. 5a). The glacial downcore samples have higher dissimilarities (Fig. 5a). Possible explanations for these higher dissimilarities might be less good analogues in

Table 3. Q-mode factor analysis of MD012404 fauna abundance data. Major factor scores are marked in bold and underline. Three factors explain 98% of the total variance.

Foraminifera species	F1	F2	F3
<i>Orbulina universa</i>	0.021	0.012	-0.013
<i>Globigerinoides conglobatus</i>	-0.011	0.030	0.001
<i>Globigerinoides ruber</i>	0.096	<u>0.447</u>	0.073
<i>Globoturborotalita tenellus</i>	0.011	0.043	-0.003
<i>Globigerinoides sacculifer</i>	0.000	0.192	-0.020
<i>Sphaeroidinella dehiscens</i>	-0.001	0.004	-0.004
<i>Globigerinella aequilateralis</i>	0.009	0.036	-0.004
<i>Globigerinella calida</i>	0.025	0.110	0.002
<i>Globigerina bulloides</i>	0.223	0.185	<u>0.934</u>
<i>Globigerina falconensis</i>	-0.001	0.032	-0.010
<i>Beela digitata</i>	0.002	0.003	-0.003
<i>Globoturborotalita rubescens</i>	0.021	0.020	0.028
<i>Turborotalita humilis</i>	-0.001	0.001	-0.000
<i>Globigerina quinqueloba</i>	0.025	-0.007	0.001
<i>Neogloboquadrina pachyderma</i> (L)	0.004	-0.001	-0.002
<i>Neogloboquadrina dutertrei</i> *	<u>0.954</u>	0.039	-0.262
<i>Globoquadrina conglomerata</i>	-0.015	0.045	-0.017
<i>Pulleniatina obliquiloculata</i>	-0.124	<u>0.414</u>	-0.100
<i>Globotalia inflata</i>	0.056	-0.028	0.035
<i>Globotalia truncatulinoides</i> (L)	0.001	-0.001	-0.000
<i>Globotalia truncatulinoides</i> (R)	0.017	-0.007	0.004
<i>Globotalia crassaformis</i>	0.003	-0.001	0.001
<i>Globotalia hirsuta</i>	0.003	0.000	-0.001
<i>Globotalia scitula</i>	0.012	-0.005	0.008
<i>Globotalia menardii</i>	-0.011	0.044	-0.007
<i>Globotalia tumida</i>	0.000	0.000	-0.001
<i>Globigerinita glutinata</i>	-0.097	<u>0.731</u>	-0.202
Variance (%)	57.651	35.868	4.411
Cumulative Var. (%)	57.651	93.519	97.929

our modern western Pacific coretop database in estimating glacial downcore samples, or “non-analogue” glacial fauna assemblages existing in core MD012404.

The estimated summer SST of core MD012404 is ~28.6°C on average during the late Holocene (Fig. 5b), and agrees well with the observed modern summer SST (NOAA 1994). This indicates the good reliability of applying RAM for estimating SST in the ECS. The LGM annual average SSTs show ~1 - 2°C decreases in comparison to the late Holocene. These results are consistent with SST estimates which were based on the use of the Modern Analog Technique (MAT) on core DGKS9603 from a northern site of the ECS (Li et al. 2001). The LGM cooling shown in core MD012404 is less pronounced than that in an alkenone SST

record from ODP1202 of the southern Okinawa Trough (Zhao et al. 2005). This discrepancy may be attributable to different sensitivity of faunal and alkenone changes to SST in the ECS (Chen et al. 2005). Our MD012404 SST record reveals large cooling on a millennial time scale. The annual SST decreased by ~3 - 4°C during Heinrich and YD events, and appears synchronous with respect to the strengthened winter monsoon events in the stalagmite record of Hulu Cave and low temperature oscillations in the ice core record from Greenland (GISP 2) (Fig. 5c). In contrast, the SST remained stable during the PME from ~3 to 5 kya.

Although high abundances of *N. dutertrei* were reported high in surface sediments in the southern part of the Okinawa Trough and are thought to be an indicator of Kuroshio

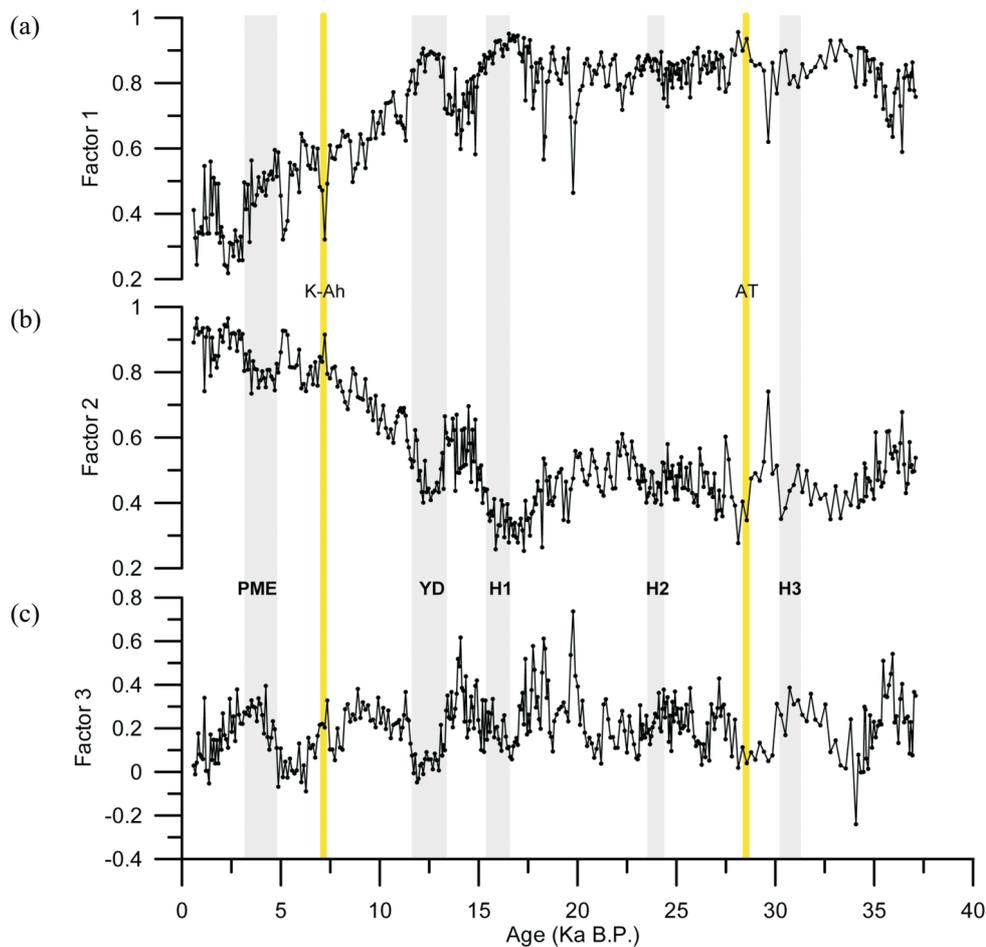


Fig. 4. Q-mode factor analysis of planktonic foraminifer fauna data. (a) Factor 1 indicates a cold water assemblage whose main contribution comes from *N. dutertrei*. (b) Factor 2 represents a warm water assemblage that is mainly composed of *G. ruber*, *G. glutinata*, and *P. obliquiloculata*. Factor 2 may indicate the influence of Kuroshio waters. (c) Factor 3 represents a coastal water assemblage whose main species is *G. bulloides*, an indicator of upwelling.

waters (Xu and Oda 1999; Ijiri et al. 2005), our observations in core MD012404 suggested a cold water mass control of the *N. dutertrei* distribution, since high abundances of this species occurred in the glacial stages from 40 to 16 kya. This observation is consistent with that reported by Li et al. (2001). In fact, our RAM SST estimates of core MD012404 were driven to relatively low values by the presence of *N. dutertrei* (Fig. 5b). This analysis indicates that *N. dutertrei* is more abundant in cold SST areas of the western Pacific. In contrast to the decline of cold water mass species, the rises of *G. ruber*, *G. glutinata*, and *P. obliquiloculata* abundances since ~16 kya could be attributed to the greater influence of warm water mass from the Pacific into the ECS since that time. The warm water mass appears to intrude with the Kuroshio. Rising global sea level conditions since ~16 kya, or synchronously strengthened East Asian summer monsoons, might explain the timing of the gradual warming observed in the ECS (Li et al. 1997; Kao et al. 2005).

Our observations on the abundance changes of two deep-dwelling species, *G. inflata* and *G. truncatulinoides*,

help interpret surface water mixing and stratification conditions in the ECS over the past 40 kyr. Both species are considered here as preferring to live in the weakly stratified upper layers of surface oceans, which are indicative of strong East Asian winter monsoon winds. The long-term trend of decreased abundances of *G. inflata* and *G. truncatulinoides* observed in our MD012404 record may suggest a long-term weakening of the East Asian winter monsoon winds, and/or increased strength of the Kuroshio intrusion into the ECS since the glacial stages. The abundance patterns of these two deep-dwelling species in MD012404 reveal more high frequency, millennial-scale oscillations, which are indicative of the instability of winter monsoon wind strength or sea level conditions in the past 40 kyrs. In particular, our MD012404 record of *G. truncatulinoides* shows minima at intervals of 4 to 8 kya (Fig. 4a) and implies a short-lived, more stratified upper layer condition in surface oceans, reflecting possibly weaker East Asian winters and/or stronger summer monsoons. An alternative explanation for this short-term event is an increase in Kuroshio water in-

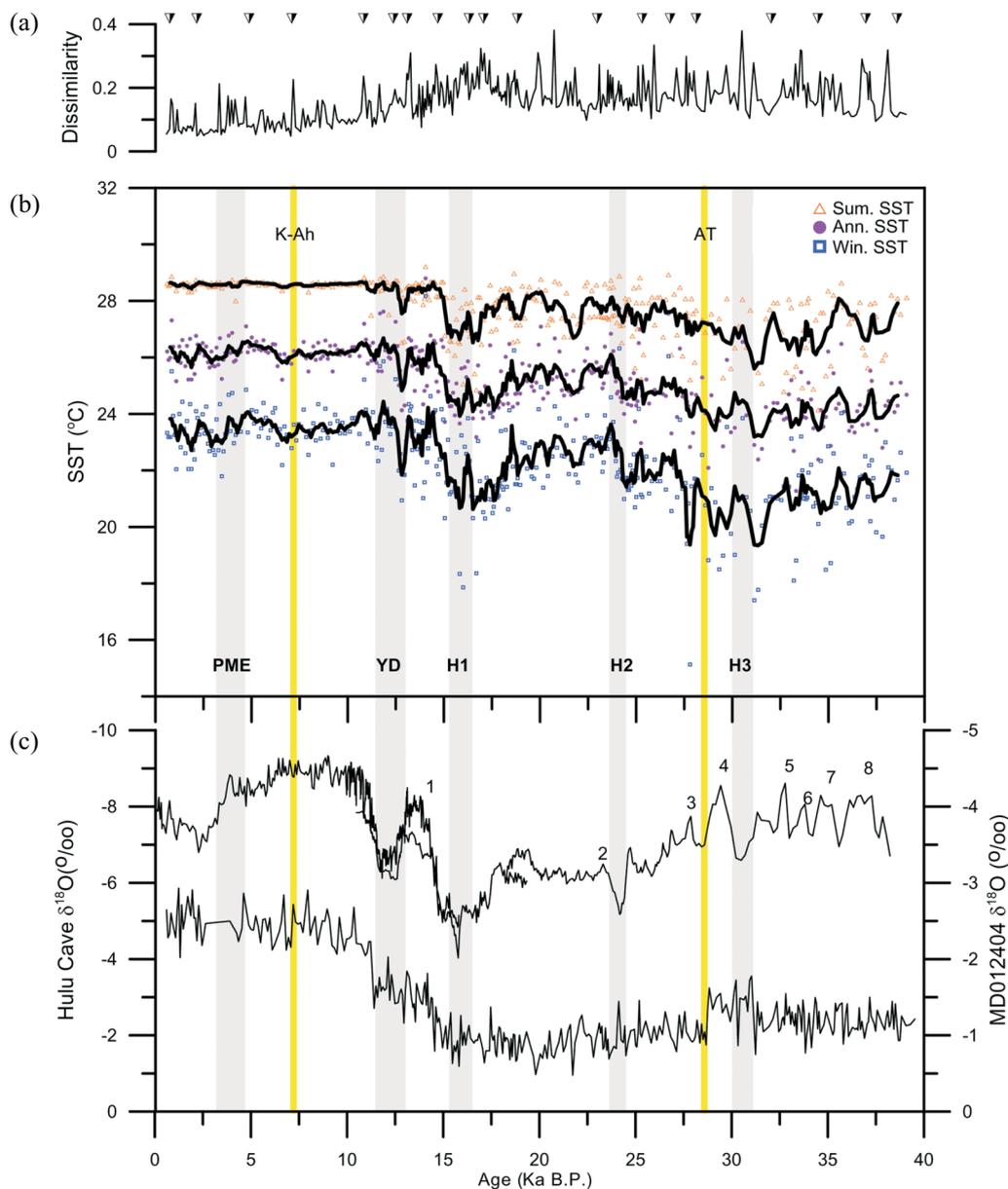


Fig. 5. Correlation between estimated RAM SST and the oxygen isotopic data from Hulu Cave. (a) Dissimilarity record; higher values mean a non-analogue situation, which is observed during glacial periods. (b) Evaluated summer (triangles), winter (squares) and annual (solid dots) SSTs of core MD012404; solid lines represent the 5 point running average values. (c) Oxygen isotopic data from Hulu Cave. Marked shadow areas represent the Heinrich events, Younger Dryas and volcanic eruptions. ¹⁴C dating ages are marked with reverse triangle above.

trusion into the ECS in response to global sea level rise in the late to middle Holocene.

Low abundances of *P. obliquiloculata* in the PME have been well-documented in many previous studies and interpreted as a weak presence and/or absence of Kuroshio waters in the ECS (Li et al. 1997; Ujiie and Ujiie 1999; Jian et al. 2000b). Our RAM SST indicates no change during the PME, suggesting that this event is not responding to atmospheric or oceanic changes in the late Holocene. We speculate that the minimum abundances of *P. obliquiloculata* were not indicative of climatic changes, although a more regional comparison (Ujiie et al. 2003) of the PME suggested an El

Niño-like condition occurring in 3 to 5 kya.

Because of the high sedimentation rate and high resolution of the record, our SST shows clear LGM and also YD cooling of ~1 - 2°C (Fig. 5b). This temperature pattern is similar to most northern hemisphere climatic records (Bond et al. 1992; Alley et al. 1993; Alley and MacAyeal 1994), suggesting a close linkage between the ECS and high latitude climate on orbital and sub-orbital time scales. Short term cooling during the episode coincident with the YD was not reported in a recent study by Sun et al. (2005). Perhaps this may be explained by the low resolution of record A7 used in Sun et al.'s (2005) study. In addition, our studies

identified a series of millennial-scale abrupt cooling of ~3–4°C in time intervals corresponding to past Heinrich events (Fig. 5c). Moreover, our SST record mirrors the structure of the monsoon stalagmite record of Hulu Cave (Wang et al. 2001) and the ice core temperature record GISP 2 from Greenland (Fig. 5c). Low SSTs coincided with strong East Asian winter monsoons and low air temperatures over Greenland in past Heinrich and stadial cooling episodes. Although strong linkages among the climatic records are clearly indicated in terms of temperature, our MD012404 oxygen isotope variations of the planktic foraminifer *G. ruber* remain stable, particularly during intervals of Heinrich event cooling. The low SSTs should be accompanied by less saline, fresh surface water in the ECS to balance the various contributions to oxygen isotopes from temperature and salinity changes. Mg/Ca SST and planktic foraminifer oxygen isotope studies (Sun et al. 2005) have consistently suggested relatively cold and fresh conditions of millennial scale changes in the ECS. Recent studies have suggested that the ITCZ played an important role in governing temperature and precipitation patterns in the tropics on millennial scales (Peterson et al. 2000; Haug et al. 2001; Wang et al. 2001; Cruz et al. 2008). During the millennial scale cold events observed in the ECS, the ITCZ is considered here to migrate southward and to bring cold air flow from the north, which in turn decreases the SST in the ECS. We hypothesize that the southward ITCZ of millennial scale changes the focus of high precipitation to the drainage area of the Yangtze River, which supplies more river runoff and fresh water into the ECS. Alternatively, increased strength of the East Asian summer monsoon during the millennial scale cooling events could be responsible for the fresh waters in the ECS, consistent with a recent finding of high rainfall in Indonesia during cooler conditions (Visser et al. 2003).

4. CONCLUSIONS

We have presented high resolution planktic foraminifer fauna assemblage data and SST records from a high sedimentation rate IMAGES core retrieved from the Okinawa Trough in the ECS. The foraminifer assemblages of cold and warm water masses, and species indicative of stratified conditions in the upper layer of surface oceans, indicate an intrusion of warm water mass with less stratified surface waters since ~16 kya in the ECS. The dominance of a warm water mass since the last glacial period possibly reflects either a rising sea level or stronger East Asian summer monsoons in the interglacial periods. The fauna variations of hydrographic-sensitive species exhibit millennial scale, high frequency oscillations, indicating the instability of the Kuroshio intrusion and/or East Asian monsoon wind strength in the past 40000 years. A noticeable PME is also observed in core MD012404, consistent with many previous fauna record studies in the Okinawa Trough and the

ECS. Although the LGM and YD are characterized by relatively cold and possibly more saline surface water conditions in the ECS, our MD012404 SST record closely tracks the structure of the monsoon stalagmite record from Hulu Cave and the ice core temperature record GISP 2 from Greenland. Low SSTs and possibly low saline, fresh surface water conditions coincided with strong East Asian winter monsoons and low air temperature over Greenland in past Heinrich and stadial cooling episodes. We hypothesize that the millennial scale migrations of ITCZ in the past 40 kyr are responsible for the SST variations observed in MD012404, and the ITCZ might change the focus of high precipitation to the drainage area of the Yangtze River during millennial scale cooling. Alternatively, East Asian summer monsoons might maintain high rainfall in the drainage area of the Yangtze River despite the cold conditions.

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