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Intense winter cooling of the surface water in the northern Okinawa Trough during the last glacial period

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Key words: thermocline temperature, TEX_{86}, MD98-2195, the East China Sea, Okinawa Trough, LGM, winter monsoon

Abstract

We generated a 42,000-year record of TEX_{86} (TEX^{L}_{86} and TEX^{H}_{86}) from core MD98-2195 to better understand changes in the hydrology of the East China Sea (ECS) in the last glacial period. The TEX_{86}-derived temperature showed an intense cooling in the last glacial period, whereas $U^{K'}_{37}$-derived spring sea surface temperature (SST) and foraminiferal Mg/Ca-derived summer SST showed a much smaller-scale cooling. The difference between the TEX_{86}- and Mg/Ca-derived temperatures was around 14°C from 19 to 16 ka and abruptly decreased to around 5°C from 16 to 13 ka. This suggests a strong winter cooling of the surface water during the last glacial period. TEX_{86}-, $U^{K'}_{37}$-, and Mg/Ca-derived temperatures were lowest at 18 to 17 ka, implying that the formation of cold water was maximized during that period. These results show that the cold water mass developed in the northern Okinawa Trough during the last glacial and the Kuroshio branch did not fully enter the northern margin of the

Okinawa Trough.

Key words: temperature, TEX_{86}, MD98-2195, the East China Sea, the last glacial period

1. Introduction

The East China Sea (ECS) is a marginal sea bounded by the Asian continent on its west, the island of Taiwan on its southwest, the Ryukyu Islands on its southeast, and Kyushu and the Korean Peninsula on its northeast and north, respectively (Fig. 1a). The hydrological evolution of the ECS and the surrounding areas since the last glacial period has been investigated using assemblages, $\delta^{18}O$, $\delta^{13}C$ and Mg/Ca data from planktonic foraminifera (e.g., Ujiié et al., 1991, 2003; Jian et al., 1996, 2000; Li et al., 1997; Shieh et al., 1997; Ujiié and Ujiié, 1999, 2006; Xu and Oda, 1999; Li et al., 2001; Ijiri et al., 2005; Sun et al., 2005; Lin et al., 2006; Chang et al., 2008; Chen et al., 2010; Kubota et al., 2010), $U^{K'}_{37}$ (e.g., Meng et al., 2002; Ijiri et al., 2005; Zhao et al., 2005; Zhou et al., 2007; Yu et al., 2008; Li et al., 2009; Wang et al., 2011), nannofossil assemblages (Ujiié et al., 1991; Ahagon et al., 1993), bulk biogenic, sulfur and lithogenic contents (Wahyudi and Minagawa, 1997; Kao et al., 2006a; Chang et al., 2009), mineralogy (Chen et al., 2011), the $\delta^{13}C$ of benthic foraminifera (Wahyudi and Minagawa, 1997), and pollen from marine cores (Kawahata and Ohshima, 2004), and modeling (Kao et al., 2006b). The ECS is characterized by a large environmental contrast between the Holocene and the last glacial period. On the basis of nannofossil and planktonic foraminifera assemblages (Ujiié et al., 1991; Ahagon et al., 19993; Ujiié and Ujiié, 1999; Ujiié et al., 2003), it was suggested that the Kuroshio did not flow into the ECS because of a blockage caused by a topographic barrier between Taiwan and Yonaguni Island. In contrast, other studies have assumed that the inflow of the Kuroshio continued during the last glacial period (e.g., Xu and Oda, 1999; Kawahata and Ohshima, 2004; Ijiri et al., 2005; Sun et al., 2005; Kao et al., 2006b; Chen et al., 2010). The difference in SST between the last glacial maximum (LGM) and the late Holocene was estimated to be 1 to 3°C in the central Okinawa Trough (Li et al., 2001; Sun et al., 2005; Zhao et al., 2005; Zhou et al., 2007; Chang et al., 2008; Chen et al., 2010) and 4 to 6°C in the northern Okinawa Trough (Xu and Oda, 1999; Ijiri et al., 2005; Kubota et al., 2010). The northern Okinawa Trough was more sensitive to climate changes than the central Okinawa Trough.

Xu and Oda (1999) discussed environmental changes in the northern Okinawa Trough during the last 36 kyr based on planktonic foraminiferan assemblages and oxygen isotopes of *Globigerina bulloides.* They recognized a period influenced by coastal water from 36 to 19.5 ka, a period influenced by coastal water and extremely low salinity from 19.5 to 10.5 ka, and a period of both high temperatures and high salinity after 10.5 ka controlled by modern open sea water related to the Kuroshio. Ijiri et al. (2005) further discussed changes in the northern Okinawa Trough hydrological conditions based on planktonic foraminiferan assemblages, the oxygen-carbon isotopes of *Globigerinoides ruber*, and $U^{K'}_{37}$. They recognized a strong upwelling period from 42 to 24 ka, a period of cold and less saline water mass from 24 to 14 ka, a transitional period from cold to warm water masses from 14 to 8 ka, and the present-day warm Kuroshio condition after 8 ka. Both studies hypothesized that the Kuroshio entered in the Okinawa Trough but weakened during the LGM and the early stages of the last deglaciation in response to the expansion of the coastal water in the northern Okinawa Trough. It is, however, not clear what forcing caused the expansion of the coastal water.

In this study, we generated a record of TEX_{86}-derived temperatures from the core MD98-2195 taken in the northern Okinawa Trough during the last 42 ky to better understand the hydrology of the northern Okinawa Trough in the last glacial period (Fig. 1a). These data, together with published data of $U^{K'}_{37}$-derived SST from the same core (Ijiri et al., 2005) and planktonic foraminiferal Mg/Ca-derived SST data from the nearby KY07-04 PC-1 core (Kubota et al., 2010), provide surface and subsurface temperature records for the last 42 kyr that can be used to assess changes in the hydrology of the northern Okinawa Trough.

Although the Holocene record of TEX_{86} at a nearby site is reported by Nakanishi et al. (submitted to Journal of Quaternary Science), this is the first report of the TEX_{86} record that extends to the last glacial period in the ECS

2. Modern oceanography of the study site

Today, the hydrology of the ECS is affected by changes in the strength of the Kuroshio and the East Asian monsoon. The Kuroshio is a western boundary current in the western North Pacific Ocean that transports warm, saline water northward and forms temperature and salinity gradients by mixing with cool, less saline water in the ECS (Ichikawa and Beardsley, 2002). Summer monsoon precipitation over south and central China provides freshwater discharge to the ECS, where a less saline surface layer develops. Winter monsoon winds cool and mix the water in the Yellow Sea (YS) and the western ECS, forming cold bottom water on the continental shelf in the ECS and YS (Uda, 1934; Ichikawa and Beardsley, 2002; Zhang et al., 2008). Under intense winter cooling, the YS and the ECS are well mixed in the upper 100 m. Because the thermal inertia of a water column on the shelf is linearly proportional to the bottom depth, which determines the cooling rate of the water column, the winter SST is lower in the shallower shelf than in the deeper shelf (Xie et al., 2002).

At the study site, warm, saline Kuroshio water meets the less saline Changjiang Diluted Water (CDW)/Yellow Sea Central Cold Water (YSCCW). The Kuroshio carries warm and saline water along the Ryukyu Islands. There is a clear boundary between the shelf water and warm Kuroshio water in winter (Fig. 1b). Temperature and salinity are nearly constant from surface to 100 meters depth at the study site. In summer, less-saline water originating from the CDW mixes with the sea-surface water, and a thermocline develops mainly due to radiative heating by insolation. As a result, the spatial temperature variation is small at the surface. At 50-m depth, the cold and less saline YSCCW spreads over the continental shelf. This water mass is formed in the YS in winter cooling, reaches to the northern Okinawa

Trough by southeastward advection and continues to exist from spring to fall (Uda, 1934; Ichikawa and Beardsley, 2002; Zhang et al., 2008).

The maximum SST near the core site is 28.3°C in August, and the minimum is 17.5°C in February (Fig. 2b; Japan Oceanographic Data Center; http://www.jodc.go.jp/index.html). SSS reaches a maximum value of 34.7 (practical salinity scale) in February and a minimum value of 33.2 in July when discharge from the Changjiang (Yangtze River) peaks.

3. Samples and methods

3.1. Study cores and age-depth model

During the IMAGES IV cruise in 1998, a 33.65-m-long giant piston core (MD98-2195) was collected from a water depth of 746 m on the northern slope of the Okinawa Trough at 31°38.33'N, 128°56.63'E (Fig. 1a). The sediment of MD98-2195 consists of olive-colored silty clay with sandy intervals at 15.28 to 15.30 m depth (Ijiri et al., 2005). Two ash layers, Kikai-Akahoya (K-Ah) and Aira-Tanzawa (AT), are intercalated at depths of 5.1 to 6.0 m and 21.8 to 22.9 m, respectively.

An age model in calendar years (Fig. 3; Ijiri et al., 2005) was created from the AMS ^{14}C ages of fourteen samples of the planktonic foraminifera *Neogloboquadrina dutertrei* and/or *Globigerina bulloides* and two ash layers: K-Ah (7.3 ka; Kitagawa et al., 1995) and AT (25.9 ka; Kitagawa and van der Plicht, 1998). The calendar age was converted using the CALIB5.0 program and dataset Marine04 (Hughen et al., 2004), with local corrections for a surface-ocean reservoir age (delta-R) of 0 years.

A total of 71 samples were collected from core MD98-2195 between the core top and a depth of 33.63 m (0–42.0 ka).

3.2. Analytical methods

Glycerol dialkyl glycerol tetraethers (GDGTs) were analyzed following Yamamoto and

Polyak (2008). Lipids were extracted (3 x) from a freeze-dried sample using a DIONEX Accelerated Solvent Extractor ASE-200 at 100°C and 1000 psi for 10 min with 11 ml of CH_2Cl_2/CH_3OH (6:4) and then concentrated. The extract was separated into four fractions using column chromatography (SiO_2 with 5% distilled water; i.d., 5.5 mm; length, 45 mm): F1 (hydrocarbons), 3ml hexane; F2 (aromatic hydrocarbons), 3 ml hexane–toluene (3:1); F3 (ketones), 4 ml toluene; F4 (polar compounds), 3 ml toluene–CH_3OH (3:1). An aliquot of F4 was dissolved in hexane-2-propanol (99:1) and filtered.

GDGTs in F4 were analyzed using high performance liquid chromatography-mass spectrometer (HPLC-MS) with an Agilent 1100 HPLC system connected to a Bruker Daltonics micrOTOF-HS time-of-flight mass spectrometer. Separation was conducted using a Prevail Cyano column (2.1 x 150 mm, 3μm; Alltech) maintained at 30˚C following the method of Hopmans et al. (2000) and Schouten et al. (2007). Conditions were: flow rate 0.2 ml/min, isocratic with 99% hexane and 1% 2-propanol for the first 5 min followed by a linear gradient to 1.8% 2-propanol over 45 min. Detection was achieved using atmospheric pressure, positive ion chemical ionization-MS (APCI-MS). The spectrometer was run in full scan mode (*m/z* 500−1500). Compounds were identified by comparing mass spectra and retention times with those of GDGT standards (obtained from the main phospholipids of *Thermoplasma acidophilum* via acid hydrolysis) and those in the literature (Hopmans et al., 2000). Quantification was achieved by integrating the summed peak areas in the $(M+H)^+$ and the isotopic $(M+H+1)^+$ chromatograms. TEX_{86} and TEX_{86}^{H} (applicable to warm water) were calculated from the concentrations of GDGT-1, GDGT-2, GDGT-3 and a regioisomer of crenarchaeol using the following expressions (Schouten et al., 2002; Kim et al., 2010):

$$TEX_{86} = ([\text{GDGT-2}]+[\text{GDGT-3}]+[\text{Crenarchaeol regioisomer}])/([\text{GDGT-1}]+[\text{GDGT-2}]+[\text{GDGT-3}]+[\text{Crenarchaeol regioisomer}])$$

$$TEX_{86}^{H} = \log(TEX_{86})$$

TEX^{L}_{86}, applicable in cooler water, was calculated from the concentrations of GDGT-1, GDGT-2 and GDGT-3 using the following expression (Kim et al., 2010):

$$TEX^{L}_{86} = \log \{[GDGT\text{-}2] / ([GDGT\text{-}1]+[GDGT\text{-}2]+[GDGT\text{-}3])\}$$

Temperature was calculated according to the following equation based on a global core top calibration (Kim et al., 2010):

$$T = 68.4TEX^{H}_{86} + 38.6 \text{ (when } T > 15°C)$$

$$T = 67.5TEX^{L}_{86} + 46.9 \text{ (when } T < 15°C)$$

where T = temperature [°C]; The standard errors averaged 0.7°C.

4. Results

The temperatures calculated from TEX^{H}_{86} were a maximum of 3°C lower than those from TEX^{L}_{86} (Fig. 4). Kim et al. (2010) recommended that TEX^{H}_{86}, which includes the abundance of crenarchaeol regio-isomer, be used in tropical and subtropical regions (>15°C) and that TEX^{L}_{86}, which excludes the abundance of crenarchaeol regio-isomer, be used in polar and subpolar regions (<15°C) because crenarchaeol regio-isomer plays a more important role for temperature adaptation in subtropical than in subpolar oceans. Because TEX^{L}_{86}- and TEX^{L}_{86}-derived temperatures exceeded 15°C at 11.5 ka, we use TEX^{L}_{86} from 42 ka to 11.5 ka and TEX^{H}_{86} after 11.5 ka for further discussion in this study.

The TEX_{86}-derived temperature fluctuated around 15°C from 42 to 27 ka, decreased to 9°C from 27 to 18 ka, increased to 18°C from 18 to 13 ka, and gradually increased to 22°C from

13 ka to the present (Fig. 4). The TEX^{H}_{86}- and TEX^{L}_{86}-based temperatures at the core-top sample (surface sediment, 0–1 cm) of core PL-1 are 22.6°C and 22.8°C, respectively. These temperatures agreed with mean annual SST (22.4°C; Japan Oceanographic Data Center; available at http://www.jodc.go.jp/index.html), the SSTs in May and November or the temperature from June to November at depths of 50–70 m (Fig. 2).

Branched and isoprenoid tetraether (BIT) index values (Hopmans et al., 2004) ranged from 0.001 to 0.005 in the samples analyzed (Fig. 5), indicating a low contribution of terrestrial soil organic matter at the study site over the last 42 kyr. Weijers et al. (2006) noted that samples with high BIT values (> 0.4) may show anomalously high TEX_{86}-derived temperatures. This concern is, however, not relevant for the samples used in this study. BIT values showed double maxima at 39 ka and 15 ka (Fig. 5), indicating an enhanced input of soil organic matter.

5. Discussion

5.1. Glacial–interglacial contrast in water temperature

The temperatures estimated using TEX_{86} differed from those obtained using $U^{K'}_{37}$ from the study core (Ijiri et al., 2005) and the Mg/Ca ratio of the planktonic foraminifera *Globigerinoides ruber* from the nearby KY07-04 PC-1 core (Kubota et al., 2010) (Fig. 4). The TEX_{86}-derived temperatures were approximately 21°C (TEX^{H}_{86}) in the late Holocene and 13°C (TEX^{L}_{86}) in the LGM, a 8°C difference (Fig. 4). In contrast, the Mg/Ca-derived temperatures were 26°C in the late Holocene and 22°C in the early deglaciation, a 4°C difference, and the $U^{K'}_{37}$-derived temperatures were 24°C in the late Holocene and 21°C in the LGM, a 3°C difference (Fig. 4).

The Mg/Ca-derived temperature is assumed to indicate SST from May to August, based on the core-top value (Kubota et al., 2010) and seasonal variation in the sinking flux (Xu et al., 2005). The $U^{K'}_{37}$-derived temperature for the core-top sample of core PL-1 is 22.3°C. This temperature is similar to the mean annual SST (22.4°C; Japan Oceanographic Data Center; available at http://www.jodc.go.jp/index.html) and the SST in May and November at this site (Fig. 2). Analysis for particulate organic matter in May showed a maximal concentration of alkenones between depths of 5 and 20 m, and the $U^{K'}_{37}$ values were consistent with the in situ water temperature (Nakanishi et al., submitted to Journal of Oceanography). A one-year time-series sediment trap experiment indicated that the sinking flux of *Emiliania huxleyi* was maximal from March to May (Tanaka et al., 2003). These observations suggest that the $U^{K'}_{37}$ reflects the SST in spring.

The season and depth of GDGT production in the ECS are not clear. The TEX^{H}_{86}- and TEX^{L}_{86}-based temperatures (22.6°C an 22.8°C, respectively) at the core-top sample of core PL-1 agreed with mean annual SST, the SSTs in May and November, and the temperature from June to November at depths of 50–70 m (Fig. 2) TEX_{86} is less likely to reflect the SST in a specific short period such as May or November for the following two reasons. First, analysis of GDGTs in particulate organic matter sampled during the spring bloom in May 2008 in the study area (Nakanishi et al., submitted) showed a low GDGT concentration and lower TEX_{86}-derived temperature than in situ temperature in the surface water column (< 20m), suggesting that TEX_{86} did not reflect the SST in May at the study site. Second, a sediment-trap study in the western North Pacific showed nearly constant TEX_{86} values in sinking particles, roughly corresponding to the mean annual SST throughout the entire year, although there was a large seasonal variation in SST, implying that GDGTs produced in different seasons were suspended and well mixed in the surface water (Yamamoto et al., 2012). These observations suggest that TEX_{86} reflects the average temperature in multiple seasons rather than the temperature in a specific time interval. This property is different from that of $U^{K'}_{37}$ and foraminiferal Mg/Ca, which reflects the temperature in the bloom and growing period (spring, and spring to summer in the ECS, respectively). Thus, the most likely interpretation is that TEX_{86} reflects either mean annual SST or summer subsurface water temperature. Although TEX_{86} is usually thought to reflect SST (Schouten et al., 2002; Kim et al., 2008; 2010), a sediment-trap study in the Santa Barbara Basin found that TEX_{86} reflected subsurface rather than surface temperatures (Huguet et al., 2006b). The TEX_{86} in tropical North Atlantic sediments was also assumed to reflect subsurface water temperature (Lopes dos Santos et al., 2010). Analysis of particulate organic matter collected in May 2008 in the northern Okinawa Trough showed a broad peak in GDGT concentrations at depths between 50 and 100 m and TEX_{86} values consistent with local water temperature at those depths, which suggests in situ production of GDGTs in the 50–100 m depth interval (Nakanishi et al., submitted). This observation indicates possible production of GDGTs in the thermocline. TEX_{86}-derived temperatures from surface sediments from the southern ECS were 0–2°C lower than mean annual SSTs (Zhu et al., 2011), whereas those from the YS and the northern SCS were much lower than the mean annual SSTs and corresponded to winter SSTs or subsurface water temperatures (Kyun-Hoon Shin, unpublished data). Therefore, the possibility that TEX_{86} reflects thermocline temperature cannot be ignored in the ECS.

Although it is not clear whether TEX_{86} reflects the mean annual SST or the summer thermocline temperature, interpretation of TEX_{86} variation is possible because both temperatures are determined by a common forcing, as discussed below. The site of this study is located east of the contact zone between the YSCCW/CDW and the KWS, and the southward migration of the YSCCW was detected by hydrographical measurements at the station west of Jeju Island (Zhang et al., 2008). A steep temperature gradient in the northern Okinawa Trough suggests the influence of the YACCW/CDW at the study site (Fig. 1b and c). In the modern summer at a depth of 50 m, the cold and relatively less saline YSCCW spreads over the continental shelf of the YS and the ECS (Fig. 1b). This water mass forms in the YS as a result of winter cooling and reaches the northern Okinawa Trough by advection, where it exists from spring until fall (Ichikawa and Beardsley, 2002; Zhang et al., 2008). Because the summer thermocline temperature is linked to winter SST, it is also a consequence of winter cooling. Although it is not clear whether TEX_{86} reflects the mean annual SST or the summer thermocline temperature, TEX_{86} likely responds to the surface cooling of the YS and/or the ECS by the East Asian winter monsoon.

The difference between the TEX_{86}- and Mg/Ca-derived temperatures was around 14°C from 19 to 16 ka and abruptly decreased to around 5°C from 16 to 13 ka (Fig. 4). In the case that TEX_{86} reflects the summer thermocline temperature, this change suggests that the summer thermocline was more developed in the last glacial period than in the Holocene. A steep gradient between surface and subsurface temperatures (24°C at 5 m, and 7°C at 50 m in in July in the northern YS; Zhang et al., 2008) is currently observed in the YS in the summer. In the case that TEX_{86} reflects SST, it is suggested that the seasonal difference in SST was larger in the last glacial period than in the Holocene. A large seasonal SST difference (ca. 18°C at 5 m depth in the northern YS; Zhang et al., 2008) is currently observed in the YS as well. The modern YS is a potential analog of the northern Okinawa Trough in the LGM.

In the last glacial period, the continental shelf of the present ECS was largely exposed due to a low sea level stand (maximum 130 m), and the study site was located near the continent (Fig. 6). Because the thermal inertia of a water column on the shelf is linearly proportional to the bottom depth (Xie et al., 2002), winter monsoon winds could have efficiently formed a cold water mass near the study site in the LGM, whereas the surface water would have been warmed by insolation and by heat exchange with the atmosphere during spring and summer. The northern Okinawa Trough was hydrologically characterized by a strong cooling of the surface water during the winter and a well-developed halocline during the summer (Xu and Oda, 1999; Ijiri et al., 2005). This resulted in the large difference between Mg/Ca-derived and TEX_{86}-derived temperatures in the northern Okinawa Trough.

5.2. Temperature changes during the last deglaciation

TEX_{86}, $U^{K'}_{37}$, and planktonic foraminiferal Mg/Ca data showed similar variation in estimated temperature for the study site (Fig. 4), despite differences in the amplitudes of variation. The temperatures gradually decreased from 42 to 18 ka, were lowest at 18 to 17 ka, and abruptly increased from 17 to 13 ka, centered at 14.5 ka (Fig. 4). This pattern was also common in the central Okinawa Trough (Li et al., 2001; Zhao et al., 2005; Sun et al., 2005; Zhou et al., 2007; Chang et al., 2008; Chen et al., 2010). At the study site, winter SST and the summer temperature at the thermocline are governed by the mixing of the cold shelf water (CDW and/or YSCCW) and Kuroshio water. Decreased TEX_{86} at 17–18 ka is thus attributable either to the intensification of the Kuroshio or to shrinkage of the CDW and the YSCCW. A weakening of the Kuroshio jet during the last deglaciation was suggested based on a SST record from offshore central Japan (Yamamoto et al., 2005; Yamamoto, 2009). This correspondence suggests that the weakening of the Kuroshio is the first possible factor affecting the TEX_{86} in the northern Okinawa Trough.

In addition, a similar pattern was observed in the TEX_{86} record from the northern South China Sea (Shintani et al., 2011). The paleotemperature difference between the northern South China Sea and the Sulu Sea suggested that the East Asian winter monsoon gradually intensified after 21 ka, maximized at 12 ka, and weakened toward the late Holocene (Shintani et al., 2008). The paleotemperature gradient between the western and eastern margins of the South China Sea suggested that the East Asian winter monsoon gradually intensified after 21 ka, maximized during the Oldest Dryas and Younger Dryas periods, and weakened towards the late Holocene (Huang et al., 2011). Changes in the TEX_{86}-derived temperatures at the study site are roughly consistent with changes in the East Asian winter monsoon inferred from paleotemperature records from the South China Sea. Because the South China Sea does not suffer a direct influence of Kuroshio variation, the intensity of the East Asian winter monsoon is the second factor affecting TEX_{86} in the study site.

In contrast to the South China Sea, the TEX_{86} record from the study site did not show a significant cooling in the Younger Dryas period. The formation of cold water in winter is generally more active in shallow shelf areas than in deeper areas. The source area of the cooled water shifted westward far from the study site due to marine transgression during the Younger Dryas period and the TEX_{86}-derived temperature became insensitive to changes in the intensity of the East Asian winter monsoon. The Younger Dryas cooling thus did not decrease TEX_{86} significantly in the study site. The formation of cold water gradually intensified from 42 to 18 ka due to both a low sea level stand and a stronger winter monsoon, maximized at 18 to 17 ka, abruptly weakened from 17 to 13 ka due to a marine transgression, and then gradually weakened afterwards. Therefore, we suggest that the formation of cold water in the northern Okinawa Trough was regulated by a combination of the intensity of the Kuroshio, the intensity of the East Asian winter monsoon and the proximity of the coast.

5.3. Oceanographic linkage with the Sea of Japan

The northern Okinawa Trough is the source region of the Tsushima Warm Current that flows in the Sea of Japan (Fig. 1b and c). The Sea of Japan was semi-isolated, well stratified and anoxic from 24 to 18 ka, resulting in the deposition of a thick dark layer (Oba et al., 1991; Tada et al., 1999). Oba et al. (1991) suggested that Huanghe (Yellow River) flowed into the Sea of Japan, forming less saline surface water. Tada et al. (1999) assumed that the freshwater inputs of the Changjiang and Huanghe rivers formed less saline water in the paleo-ECS that flowed into the Sea of Japan.

Today, the Kuroshio branch current west of Kyushu (KBCWK) passes through the western flank of the northern Okinawa Trough (Fig. 1b and c; Ichikawa and Beardsley, 2002) and becomes the Tsushima Warm Current by mixing with the ECS water. Xu and Oda (1999) demonstrated that the less saline and low temperature species *Globigerina quinqueloba* frequently occurred from 19.5 to 10.5 ka in the northern Okinawa Trough. Ijiri et al. (2005) subsequently showed the presence of a cold and less saline water mass in the northern Okinawa Trough from 24 to 14 ka, based on high abundance of *Neogloboquadrina pachyderma*, *Neogloboquadrina incompta,* and *Globigerina quinqueloba*. They further indicated the freshwater influence on the surface water during this period based on the $\delta^{18}O$ of planktonic foraminifera. Our study demonstrates the development of a cold water mass in the northern Okinawa Trough during the LGM (Fig. 6). These results suggest that the KBCWK did not fully enter the northern Okinawa Trough. Because the KBCWK weakened, the inflow of saline water into the Sea of Japan decreased, resulting in the development of a halocline in the Sea of Japan during the LGM.

6. Conclusions

The TEX_{86}-derived temperature showed intense cooling in the last glacial period, whereas $U^{K'}_{37}$-derived spring sea surface temperature (SST) and Mg/Ca-derived summer SST showed much smaller-scale cooling. In the last glacial period, the hydrology of the northern Okinawa Trough was characterized by strong cooling of the surface water in winter and the development of cold subsurface water during summer.

TEX_{86}-, $U^{K'}_{37}$-, and planktonic foraminiferal Mg/Ca-derived temperatures gradually decreased from 42 to 18 ka, were lowest at 18 to 17 ka, abruptly increased from 17 to 13 ka centered at 14.5 ka, reflecting changes in cold water formation in the northern Okinawa Trough

During the LGM, the development of a cold-water mass in the northern Okinawa Trough could have prevented the saline Kuroshio water from flowing into the northern Okinawa Trough and the Sea of Japan, resulting in the development of a halocline in the Sea of Japan during the LGM.

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PC-1 core, respectively. We also thank Min-Te Chen and two anonymous reviewers for their constructive comments. We appreciate Prof. Chi-Yue Huang for his contributions to the studies on East China Sea paleoceanography. This study was supported by a grant-in-aid for Scientific Research (A) the Japan Society for the Promotion of Science, No. 19204051 (to MY).

References

Ahagon, N., Tanaka, Y., Ujiié, H., 1993. *Florisphaera profunda*, a possible nanoplankton indicator of late Quaternary changes in sea-surface turbidity at the northern margin of the Pacific. Marine Micropaleontology 22, 255–273.

Chang, Y.-P., Wang, W.-L., Yokoyama, Y., Matsuzaki, H., Kawahata, H., Chen, M.T., 2008. Millennial-scale planktic foraminifer faunal variability in the East China Sea during the past 40000 years (IMAGES MD012404 from the Okinawa Trough). Terrestrial, Atmospheric and Oceanic Sciences 19, 389–401.

Chang, Y.-P., Chen, M.-T., Yokoyama, Y., Matsuzaki, H., Thompson, W.G., Kao, S.J., Kawahata, H., 2009. Monsoon hydrography and productivity changes in the East China Sea during the past 100,000 years: Okinawa Trough evidence (MD012404). Paleoceanography 24, PA3208.

Chen, M.-T., Lin, X.P., Chang, Y.-P., Chen, Y.-C., Lo, L., Shen, C.-C., Yokoyama, Y., Oppo, D.W., Thompson, W.G., Zhang, R., 2010. Dynamic millennial-scale climate changes in the northwestern Pacific over the past 40,000 years. Geophysical Research Letters 37, L23603.

Chen, H.F., Chang, Y.P., Kao, S.J., Chen, M.T., Song, S.R., Luo, L.W., Wen, S.Y., Yang, T.N., Lee, T.Q., 2011. Mineralogical and geochemical investigations of sediment-source region changes in the Okinawa Trough during the past 100 ka (IMAGES core MD012404): Journal of Asian Earth Sciences 40, 1238-1249.

Hopmans, E.C., Schouten, S., Pancost, R., van der Meer, M.T.J., Sinninghe Damsté, J.S., 2000.

Analysis of intact tetraether lipids in archaeal cell material and sediments by high performance liquid chromatography/atmospheric pressure chemical ionization mass spectrometry. Rapid Communications in Mass Spectrometry 14, 585–589.

Hopmans, E.C., Weijers, J.W.H., Schefuss, E., Herfort, L., Sinninghe Damsté, J.S., Schouten, S., 2004. A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. Earth and Planetary Science Letters 224, 107–116.

Huang, E., Tian, J., Steinke, S., 2011. Millennial-scale dynamics of the winter cold tongue in the southern South China Sea over the past 26 ka and the East Asian winter monsoon. Quaternary Research 75, 196–204.

Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G,, Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. MARINE04 marine radiocarbon age calibration, 0 – 26 cal kyr BP. Radiocarbon 46, 1059–1086.

Huguet, C., Kim, J.-H., Sinninghe Damsté, J.S., Schouten, S., 2006. Reconstruction of sea surface temperature variations in the Arabian Sea over the last 23 kyr using organic proxies (TEX_{86} and $U^{K'}_{37}$). Paleoceanography 21, PA300S.

Ichikawa, H., Beardsley, R.C., 2002. The current system in the Yellow and East China Seas. Journal of Oceanography 58, 77–92.

Ijiri, A., Wang, L., Oba, T., Kawahata, H., Huang, C.Y., Huang, C.Y., 2005. Paleoenvironmental changes in the northern area of the East China Sea during the past 42,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 219, 239–261.

Japan Oceanographic Data Center (JODC) 1906–2003. Oceanographic data, monthly sea-surface temperature in the East China Sea, http://www.jodc.go.jp/index.html, Japan Hydrographic Association, Tokyo, Japan.

Jian, Z., Li, B., Pflaumann, U., Wang, P., 1996. Late Holocene cooling event in the western Pacific. Science in China (Series D) 39, 543–550.

Jian, Z.S., Wang, P.X., Saito, Y., Wang, L.J., Pflaumann, U., Oba, T., Cheng, X.R., 2000. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. Earth and Planetary Science Letters 184, 305–319.

Kao, S.J., Roberts, A.P., Hsu, S.C., Chang, Y.P., Lyons, W.B., Chen, M.-T., 2006a. Monsoon forcing, hydrodynamics of the Kuroshio Current, and tectonic effects on sedimentary carbon and sulfur cycling in the Okinawa Trough since 90 ka. Geophysical Research Letters 33, L05610.

Kao, S.J., Wu, C.R., Hsin, Y.C., Dai, M., 2006b. Effects of sea level changes on the upstream Kuroshio Current through the Okinawa Trough. Geophysical Research Letters 33, L16604.

Kawahata, H., Ohshima, H., 2004. Vegetation and environmental record in the northern East China Sea during the late Plistocene. Global and Planetary Change 41, 251–273.

Kim, J.H., van der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Koc, N., Hopmans, E.C., Sinninghe Damsté, J.S., 2010. New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: Implications for past sea surface temperature reconstructions. Geochimica et Cosmochimica Acta 74, 4639–4654.

Kitagawa, H., Fukusawa, H., Nakamura, T., Okamura, M., Takemura, K., Hayashida, A., Yasuda, Y., 1995. AMS ^{14}C dating of varved sediments from Lake Suigetsu, central Japan and atmospheric ^{14}C change during the late Pleistocene. Radiocarbon 37, 371– 378.

Kitagawa, H., van der Plicht, J., 1998. A 40,000-year varve chronology from Lake Suigetsu, Japan: extension of the radiocarbon curve. Radiocarbon 40, 505–516.

Kondo, M., 1985. Oceanographic investigations of fishing grounds in the East China Sea and the Yellow Sea—I, Characteristics of the mean temperature and salinity distributions measured at 50 m and near the bottom. Bulletin of Seikai Region Fishery Research Laboratory 62, 19–55 (in Japanese with English abstract).

Kubota, Y., Kimoto, K., Tada, R., Oda, H., Yokoyama, Y., Matsuzaki, H., 2010. Variations of East Asian summer monsoon since the last deglaciation based on Mg/Ca and oxygen isotope of planktic foraminifera in the northern East China Sea. Paleoceanography 25, PA4205.

Li, B., Jian, Z., Wang, P., 1997. *Pulleniatina obliquiloculata* as a paleoceanographic indicator in the southern Okinawa Trough during the last 20,000 years. Marine Micropaleontology 32, 59–69.

Li, T., Liu, Z., Hall, M.A., Berne, S., Saito, Y., Cang, S., Cheng, Z., 2001. Heinrich event imprints in the Okinawa Trough: evidence from oxygen isotope and planktonic foraminifera. Palaeogeography, Palaeoclimatology, Palaeoecology 176, 133–146.

Li, G., Sun, X., Liu, Y., Bickert, T., Ma, Y., 2009. Sea surface temperature record from the north of the East China Sea since late Holocene. Chinese Science Bulletin 54, 4507–4513.

Lin, Y.S., Wei, K.Y., Lin, I.T., Yu, P.S., Chiang, H.W., Chen, C.Y., Shen, C.C., Mii, H.S., Chen, Y.G., 2006. The Holocene *Pulleniatina* Minimum Event revisited: geochemical and faunal evidence from the Okinawa Trough and upper reaches of the Kuroshio current. Marine Micropaleontology 59, 153–170.

Lopes dos Santos, R., Prange, M., Castañeda, I.S., Schefuß, E., Mulitza, S., Schulz, M., Niedermeyer, E.M., Sinninghe Damsté, J.S., Schouten, S., 2010. Glacial–interglacial variability in Atlantic meridional overturning circulation and thermocline adjustments in the tropical North Atlantic. Earth and Planetary Science Letters 300, 407–414.

Meng, X., Du, D., Liu, Y., Liu, Z., 2002. Molecular biomarker record of paleoceanographic environment in the East China Sea during the last 35000 years. Science in China (Series D) 45, 184–192.

Nakanishi, T., Yamamoto, M., Irino, T., Tada, R., Distributions of glycerol dialkyl glycerol tetraethers, alkenones and polyunsaturated fatty acids in suspended particulate organic matter in the East China Sea. Submitted to Journal of Oceanography.

Nakanishi, T., Yamamoto, M., Tada, R., Oda, H., Centennial-scale winter monsoon variability in the northern East China Sea during the Holocene. Submitted to Journal of Quaternary Science.

Oba, T., Kato, M., Kitazato, H., Koizumi, I., Omura, A., Sakai, T., Takayama, T., 1991. Paleoenvironmental changes in the Japan Sea during the last 85,000 years. Paleoceanography 6, 499–518.

Schouten, S., Hopmans, E.C., Schefuß, E., Sinninghe Damsté, J.S., 2002. Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? Earth and Planetary Science Letters 204, 265–274.

Schouten, S, Huguet, C., Hopmans, E.C., Kienhuis, M.V.M., Sinninghe Damsté, J.S., 2007. Analytical methodology for TEX_{86} paleothermometry by high performance liquid chromatography/atmospheric pressure chemical ionization-mass spectrometry. Analytical Chemistry 79, 2940–2944.

Shieh, Y.-T., Wang, C.-H., Chen, M.-P., Yung, Y.-L., 1997. The last glacial maximum to Holocene environment changes in the southern Okinawa Trough. Journal of Asian Earth Sciences 15, 3–8.

Shintani, T., Yamamoto, M., Chen, M.-T., 2008. Slow warming of the northern South China Sea during the last deglaciation. Terrestrial, Atmospheric and Oceanic Sciences, 19, 341–346.

Shintani, T., Yamamoto, M., Chen, M.T., 2011. Paleoenvironmental changes in the northern South China Sea over the past 28,000 years: a study of TEX_{86}-derived sea surface temperatures and terrestrial biomarkers. Journal of the Asian Earth Science 40, 1221–1229.

Sun, Y., Oppo, D.W., Xiang, R., Liu, W., Gao, S., 2005. Last deglaciation in the Okinawa Trough: subtropical northwest Pacific link to northern hemisphere and tropical climate. Paleoceanography 20, A4005.

Tada, R., Irino, T., Koizumi, I., 1999. Land-ocean linkage over orbital and millennial timescales recorded in late Quaternary sediments of the Japan Sea. Paleoceanography 14, 236–247.

Tanaka, Y., 2003. Coccolith fluxes and species assemblages at the shelf edge and in the Okinawa Trough of the East China Sea. Deep-Sea Research II 50, 503–511.

Uda, M., 1934. Climatological monthly mean oceanic conditions in the Japan, Yellow, and Okhotsk Seas. Fisheries Experimental Station Report **5**, 191–236 (in Japanese).

Ujiié, H., Tanaka, Y., Ono, T., 1991. Late Quaternary paleoceanographic record from the middle Ryukyu Trench slope, Northwest Pacific. Marine Micropaleontology 18, 115–128.

Ujiié, H., Ujiié, Y., 1999. Late Quaternary course of the Kuroshio Current in the Ryukyu Arc region, northwestern Pacific Ocean. Marine Micropaleontology 37, 23–40.

Ujiié, Y., Ujiié, H., Taira, A., Nakamura, T., Oguri, K., 2003. Spatial and temporal variability of surface water in the Kuroshio source region, Pacific Ocean, over the past 21,000 years: evidence from planktonic foraminifera. Marine Micropaleontology 49, 335–364.

Ujiié, Y., Ujiié, H., 2006. Dynamic changes of the surface and intermediate waters in the Ryukyu Arc region during the past ~250,000 years: based on planktonic and benthic foraminiferal analysis of two IMAGES cores. Fossils 79, 43–59 (in Japanese with English abstract).

Wahyudi, Minagawa, M., 1997. Response of benthic foraminifera to organic carbon accumulation rates in the Okinawa Trough. Journal of Oceanography 53, 411–420.

Wang, L., Yang, Z., Zhang, R., Fan, D., Zhao, M., Hu, B., 2011. Sea surface temperature records of core ZY2 from the central mud area in the South Yellow Sea during last 6200 years and related effect of the Yellow Sea warm current. Chinese Science Bulletin 56, 1588–1595.

Weijers, J.W.H., Schouten, S., Spaargaren, O.C., Sinninghe Damsté, J.S., 2006. Occurrence and distribution of tetraether membrane in soils: Implications for the use of the BIT index and the TEX_{86} SST proxy. Organic Geochemistry 37, 1680–1693.

Xie, S.-P., Hafner, J., Tanimoto, Y., Liu, W.T., Tokinaga, H., Xu, H., 2002. Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China Seas. Geophysical Research Letters 29, 2228.

Xu, X., Oda, M., 1999. Surface-water evolution of the eastern East China Sea during the last 6,000 years. Marine Geology 156, 285–304.

Xu, X., Yamasaki, M., Oda, M., Honda, M.C., 2005. Comparison of seasonal flux variations of planktonic foraminifera in sediment raps on both sides of the Ryukyu Islands, Japan, Marine Micropaleontology 58, 45–55.

Yamamoto, M., Suemune, R., Oba, T., 2005. Equatorward shift of the subarctic boundary in the northwestern Pacific during the last deglaciation. *Geophysical Research Letters* **32**, L05609.

Yamamoto, M., 2009. Response of mid-latitude North Pacific surface temperatures to orbital forcing and linkage to the East Asian summer monsoon and tropical ocean-atmosphere interactions. Journal of Quaternary Science 24, 836-847.

Yamamoto, M., Polyak, L., 2009. Changes in terrestrial organic matter input to the Mendeleev Ridge, western Arctic Ocean, during the Late Quaternary. Global and Planetary Change 68, 30–37.

Yamamoto, M., Shimamoto, A., Fukuhara, T., Tanaka, Y., Ishizaka, J., 2012. Glycerol dialkyl glycerol tetraethers and the TEX_{86} index in sinking particles in the western North Pacific. Organic Geochemistry, http://dx.doi.org/10.1016/j.orggeochem.2012.04.010.

Yu, H., Xiong, Y., Liu, Z., Berné, S., Huang, C.-Y., Jia, G., 2008. Evidence for the 8,200 a B.P. cooling event in the middle Okinawa Trough. Geo-Marine Letters 28, 131–136.

Zhang, S.W., Wang, Q.A., Lu, Y., Cui, H., Yuan, Y.L., 2008. Observation of the seasonal evolution of the Yellow Sea Cold Water Mass in 1996–1998. Continental Shelf Research 28, 442–457.

Zhao, M., Huang, C.-Y., Wei, K.-Y., 2005. A 28,000 year $U^{K'}_{37}$ sea surface temperature record

of ODP Site 1202B, the southern Okinawa Trough. TAO 16, 45–56.
Zhou, H., Li, T., Jia, G., Zhu, Z., Chi, B., Cao, Q., Sun, R., Peng, P., 2007. Sea surface temperature reconstruction for the middle Okinawa Trough during the last glacial-interglacial cycle using C_{37} unsaturated alkenones. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 440–453.
Zhu, C., Weijers, J.W.H., Wagner, T., Pan, J.-M., Chen, J.-F., Pancost, R.D., 2011. Sources and distributions of tetraether lipids in surface sediments across a large river-dominated continental margin. Organic Geochemistry 42, 376–386.

Figure captions

Fig. 1. (a) MD98-2195 core location, (b and c) the distribution of seasonal mean winter and summer temperatures at 50 m depth, and the surface water circulation pattern in the East China Sea and the Yellow Sea (Kondo, 1985). KSW = Kuroshio Water. CDW = Changjiang Diluted Water. CCW = Chinese Coastal Water. YSCCW = Yellow Sea Central Cold Water. KBCWK = Kuroshio branch current west of Kyushu. TSWC = Tsushima Warm Current.

Fig. 2. Seasonal and monthly mean water temperatures at different depths at the study site (Japan Oceanographic Data Center; http://www.jodc.go.jp/index.html). “J” to “D” denote the months from January to December. After Nakanishi et al., submitted to Journal of Quaternary Science.

Fig. 3. Age depth model of core MD98-2195 (Ijiri et al., 2005).

Fig. 4. Variations in TEX_{86}-, TEX^{H}_{86}-, and TEX^{L}_{86}-derived thermocline temperature, $U^{K'}_{37}$-derived SST (Ijiri et al., 2005), and *Globigerinoides ruber* Mg/Ca-derived SST (Kubota et al., 2010) for the last 42 kyr from core MD98-2195. H0 = the Younger Dryas period, H1 = the Oldest Dryas period. H2 = Heinrich event 2. H3 = Heinrich event 3. H4 = Heinrich event 4.

Fig. 5. Variation in branched and isoprenoid tetraethers (BIT) index for the last 42 kyr from core MD98-2195.

Fig. 6. Schematic map showing the distributions of coastline and shallow shelf area in the East China Sea at 15 ka. The sea level was 100 m lower than the present. The cold water was presumably formed near the study site and expanded to the northern Okinawa Trough.

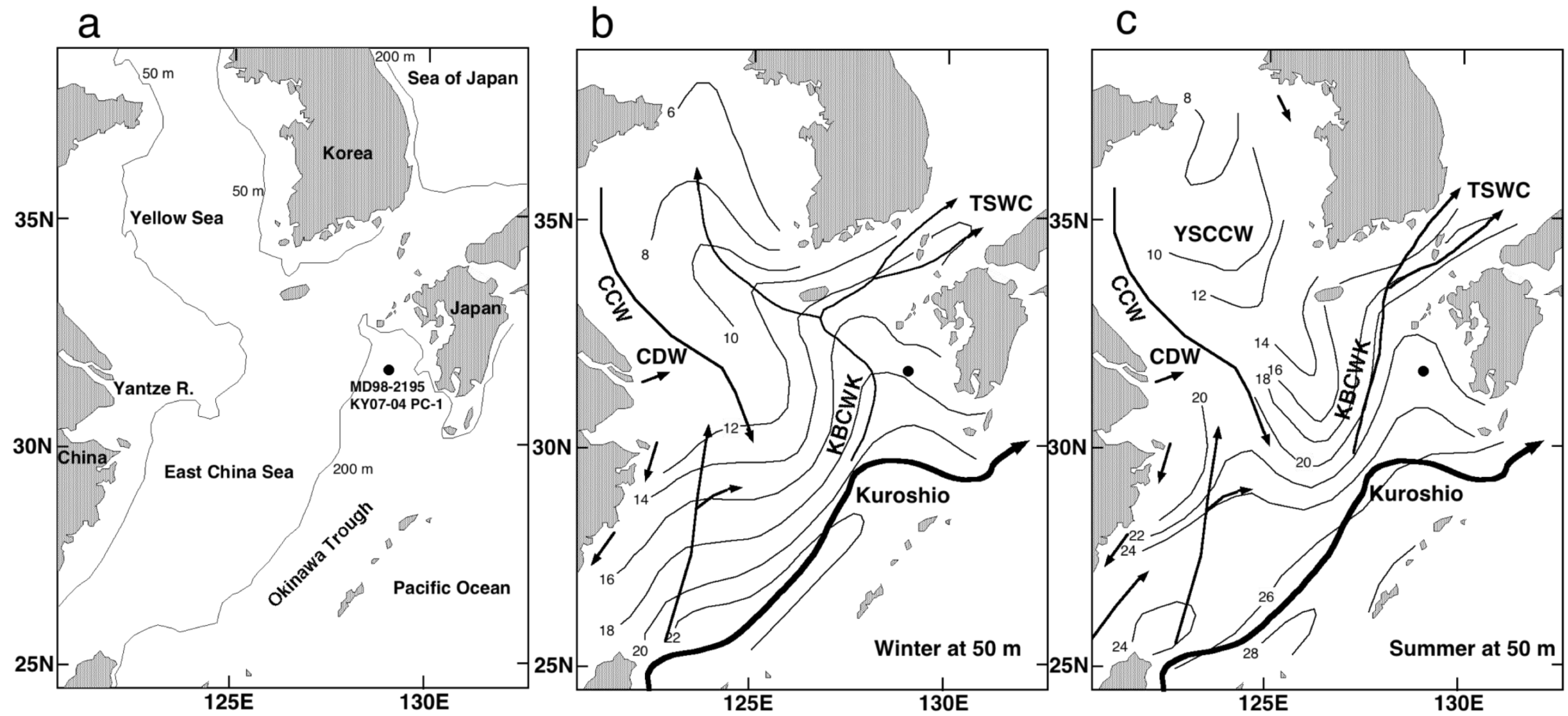
a
50 m
200 m
Sea of Japan
Korea
50 m
Yellow Sea
Japan
Yantze R.
MD98-2195
KY07-04 PC-1
China
East China Sea
200 m
Okinawa Trough
Pacific Ocean
35N
30N
25N
125E
130E
b
6
8
10
12
14
16
18
20
22
CCW
CDW
TSWC
KBCWK
Kuroshio
Winter at 50 m
c
8
10
12
14
16
18
20
22
24
26
28
YSCCW
CCW
CDW
TSWC
KBCWK
Kuroshio
Summer at 50 m

Fig. 1.

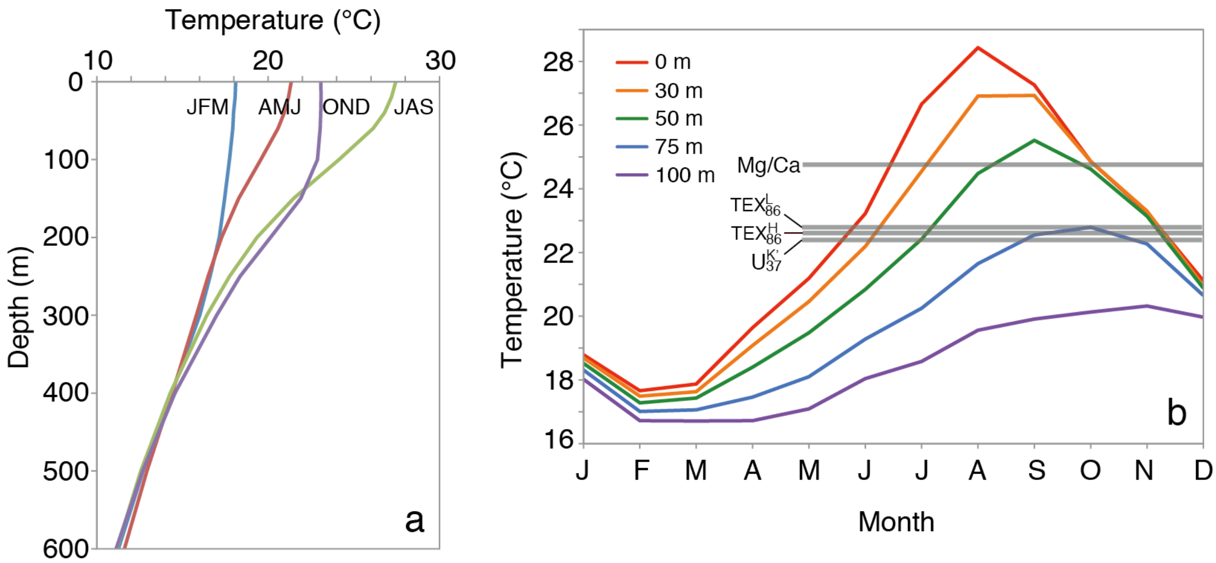

Fig. 2

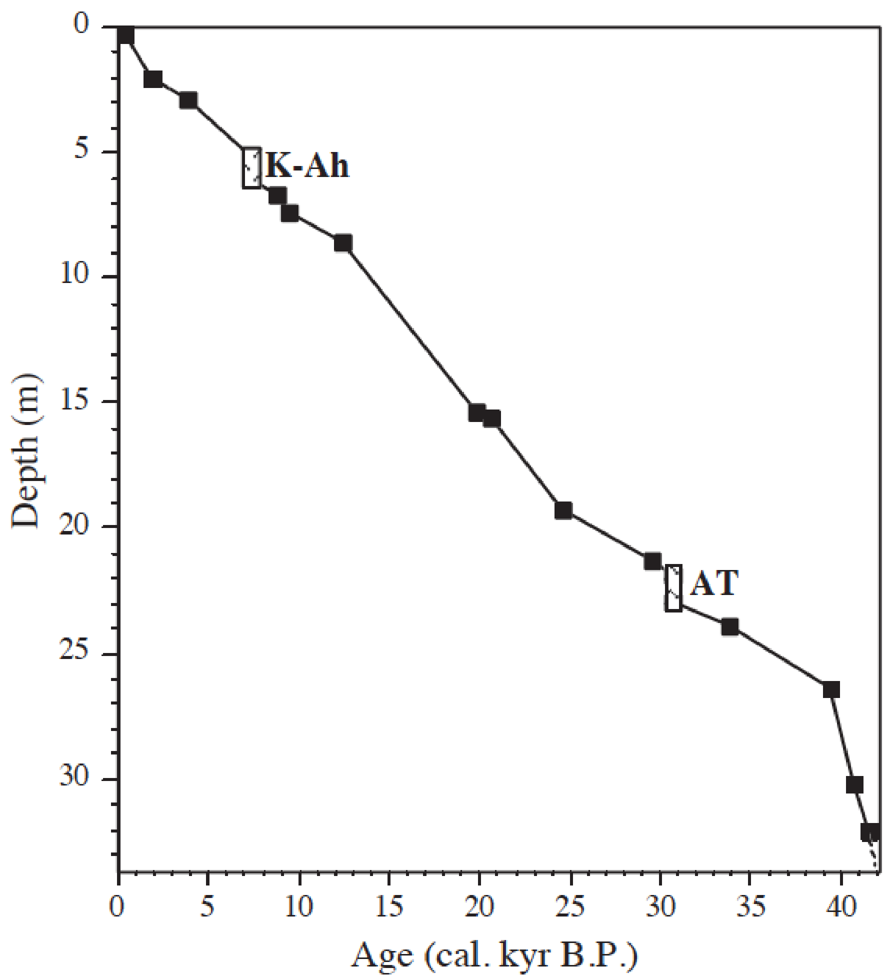

Fig. 3.

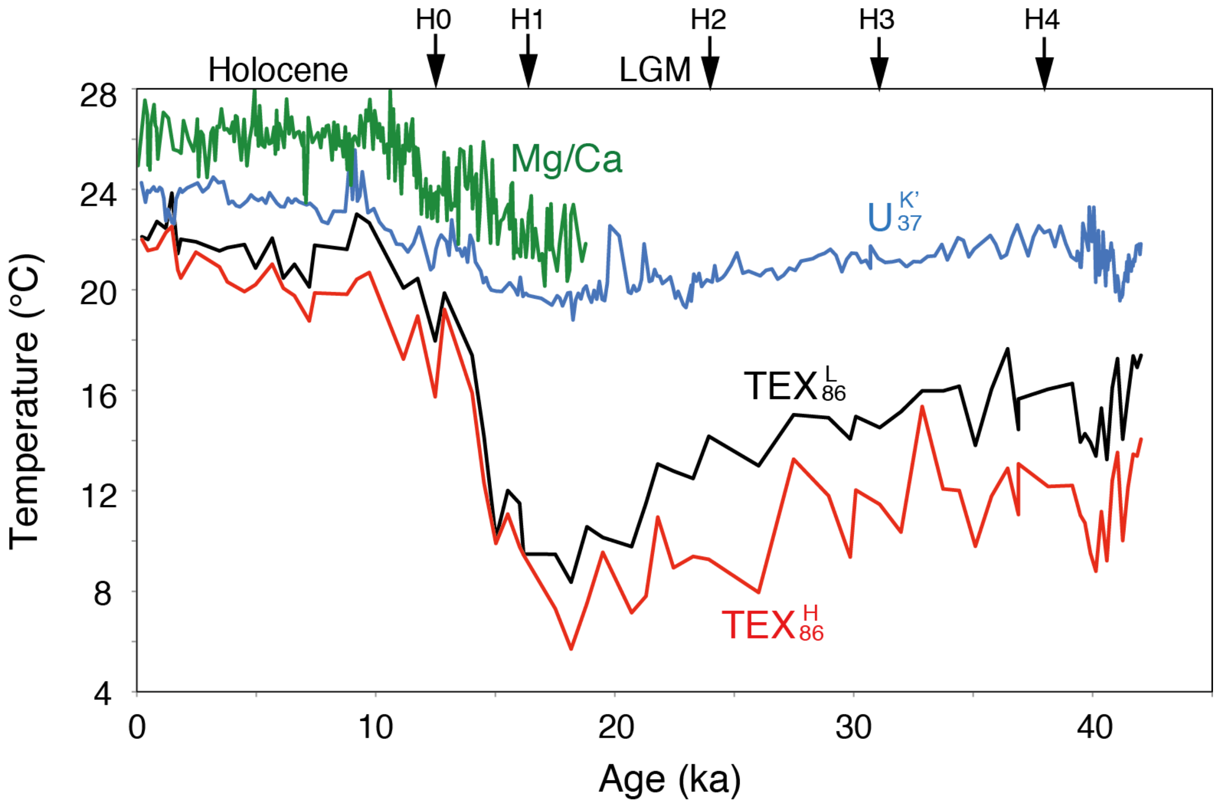
H0
H1
H2
H3
H4
Holocene
LGM
Mg/Ca
$U^{K'}_{37}$
TEX^{L}_{86}
TEX^{H}_{86}
Temperature (°C)
28
24
20
16
12
8
4
0
10
20
30
40
Age (ka)

Fig. 4.

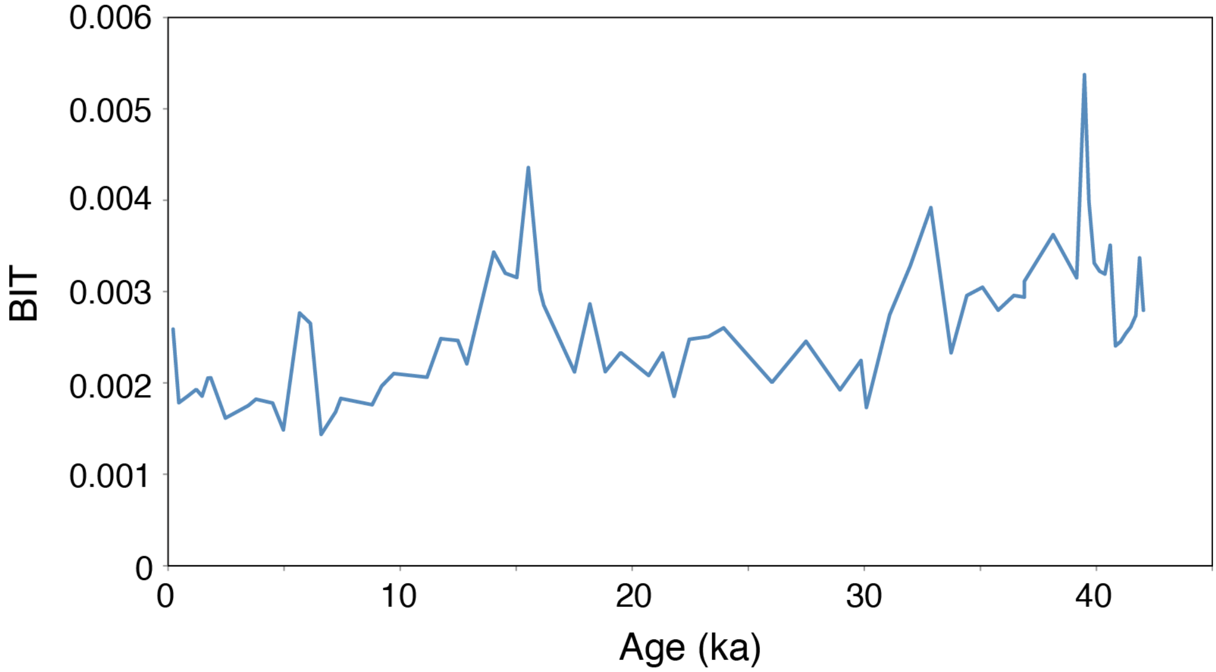
BIT
0.006
0.005
0.004
0.003
0.002
0.001
0
0
10
20
30
40
Age (ka)

Fig. 5.

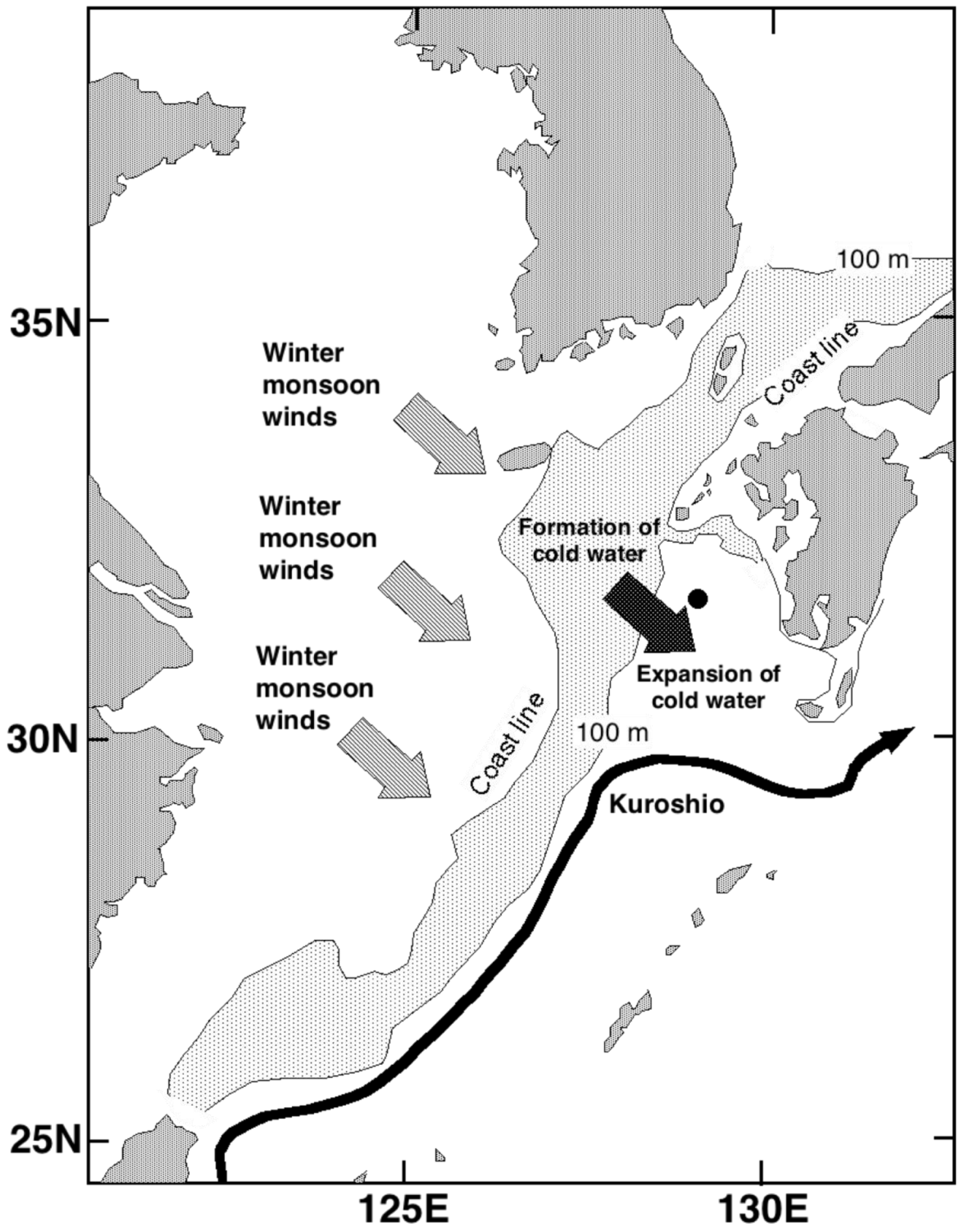
100 m
35N
Winter
monsoon
winds
Coast line
Winter
monsoon
winds
Formation of
cold water
Winter
monsoon
winds
Expansion of
cold water
Coast line
100 m
30N
Kuroshio
25N
125E
130E

Fig. 6