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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_{86}^{L} and TEX_{86}^{H}) 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 $U_{37}^{K'}$-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}-, $U_{37}^{K'}$-, 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):

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

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

156

157 TEX_{86}^{L}, applicable in cooler water, was calculated from the concentrations of GDGT-1,

158 GDGT-2 and GDGT-3 using the following expression (Kim et al., 2010):

159

160 $$TEX_{86}^{L} = \log \{[GDGT\text{-}2] / ([GDGT\text{-}1]+[GDGT\text{-}2]+[GDGT\text{-}3])\}$$

161

162 Temperature was calculated according to the following equation based on a global core top

163 calibration (Kim et al., 2010):

164

165 $T = 68.4TEX_{86}^{H} + 38.6$ (when T > 15°C)

166 $T = 67.5TEX_{86}^{L} + 46.9$ (when T < 15°C)

167

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

169

170 **4. Results**

171 The temperatures calculated from TEX_{86}^{H} were a maximum of 3°C lower than those from

172 TEX_{86}^{L} (Fig. 4). Kim et al. (2010) recommended that TEX_{86}^{H}, which includes the abundance

173 of crenarchaeol regio-isomer, be used in tropical and subtropical regions (>15°C) and that

174 TEX_{86}^{L}, which excludes the abundance of crenarchaeol regio-isomer, be used in polar and

175 subpolar regions (<15°C) because crenarchaeol regio-isomer plays a more important role for

176 temperature adaptation in subtropical than in subpolar oceans. Because TEX_{86}^{L}- and TEX_{86}^{L}

177 -derived temperatures exceeded 15°C at 11.5 ka, we use TEX_{86}^{L} from 42 ka to 11.5 ka and

178 TEX_{86}^{H} after 11.5 ka for further discussion in this study.

179 The TEX_{86}-derived temperature fluctuated around 15°C from 42 to 27 ka, decreased to 9°C

180 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_{86}^{H}- and TEX_{86}^{L}-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 $U_{37}^{K'}$ 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_{86}^{H}) in the late Holocene and 13°C (TEX_{86}^{L}) 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 $U_{37}^{K'}$-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 $U_{37}^{K'}$-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

233 temperature. Although TEX_{86} is usually thought to reflect SST (Schouten et al., 2002; Kim et
234 al., 2008; 2010), a sediment-trap study in the Santa Barbara Basin found that TEX_{86} reflected
235 subsurface rather than surface temperatures (Huguet et al., 2006b). The TEX_{86} in tropical
236 North Atlantic sediments was also assumed to reflect subsurface water temperature (Lopes
237 dos Santos et al., 2010). Analysis of particulate organic matter collected in May 2008 in the
238 northern Okinawa Trough showed a broad peak in GDGT concentrations at depths between
239 50 and 100 m and TEX_{86} values consistent with local water temperature at those depths,
240 which suggests in situ production of GDGTs in the 50–100 m depth interval (Nakanishi et al.,
241 submitted). This observation indicates possible production of GDGTs in the thermocline.
242 TEX_{86}-derived temperatures from surface sediments from the southern ECS were 0–2°C
243 lower than mean annual SSTs (Zhu et al., 2011), whereas those from the YS and the northern
244 SCS were much lower than the mean annual SSTs and corresponded to winter SSTs or
245 subsurface water temperatures (Kyun-Hoon Shin, unpublished data). Therefore, the
246 possibility that TEX_{86} reflects thermocline temperature cannot be ignored in the ECS.

247 Although it is not clear whether TEX_{86} reflects the mean annual SST or the summer
248 thermocline temperature, interpretation of TEX_{86} variation is possible because both
249 temperatures are determined by a common forcing, as discussed below. The site of this study
250 is located east of the contact zone between the YSCCW/CDW and the KWS, and the
251 southward migration of the YSCCW was detected by hydrographical measurements at the
252 station west of Jeju Island (Zhang et al., 2008). A steep temperature gradient in the northern
253 Okinawa Trough suggests the influence of the YACCW/CDW at the study site (Fig. 1b and
254 c). In the modern summer at a depth of 50 m, the cold and relatively less saline YSCCW
255 spreads over the continental shelf of the YS and the ECS (Fig. 1b). This water mass forms in
256 the YS as a result of winter cooling and reaches the northern Okinawa Trough by advection,
257 where it exists from spring until fall (Ichikawa and Beardsley, 2002; Zhang et al., 2008).
258 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

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

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

309 In contrast to the South China Sea, the TEX_{86} record from the study site did not show a
310 significant cooling in the Younger Dryas period. The formation of cold water in winter is

311 generally more active in shallow shelf areas than in deeper areas. The source area of the
312 cooled water shifted westward far from the study site due to marine transgression during the
313 Younger Dryas period and the TEX_{86}-derived temperature became insensitive to changes in
314 the intensity of the East Asian winter monsoon. The Younger Dryas cooling thus did not
315 decrease TEX_{86} significantly in the study site. The formation of cold water gradually
316 intensified from 42 to 18 ka due to both a low sea level stand and a stronger winter monsoon,
317 maximized at 18 to 17 ka, abruptly weakened from 17 to 13 ka due to a marine transgression,
318 and then gradually weakened afterwards. Therefore, we suggest that the formation of cold
319 water in the northern Okinawa Trough was regulated by a combination of the intensity of the
320 Kuroshio, the intensity of the East Asian winter monsoon and the proximity of the coast.
321
322 **5.3. Oceanographic linkage with the Sea of Japan**
323 The northern Okinawa Trough is the source region of the Tsushima Warm Current that
324 flows in the Sea of Japan (Fig. 1b and c). The Sea of Japan was semi-isolated, well stratified
325 and anoxic from 24 to 18 ka, resulting in the deposition of a thick dark layer (Oba et al.,
326 1991; Tada et al., 1999). Oba et al. (1991) suggested that Huanghe (Yellow River) flowed
327 into the Sea of Japan, forming less saline surface water. Tada et al. (1999) assumed that the
328 freshwater inputs of the Changjiang and Huanghe rivers formed less saline water in the
329 paleo-ECS that flowed into the Sea of Japan.

330 Today, the Kuroshio branch current west of Kyushu (KBCWK) passes through the western
331 flank of the northern Okinawa Trough (Fig. 1b and c; Ichikawa and Beardsley, 2002) and
332 becomes the Tsushima Warm Current by mixing with the ECS water. Xu and Oda (1999)
333 demonstrated that the less saline and low temperature species *Globigerina quinqueloba*
334 frequently occurred from 19.5 to 10.5 ka in the northern Okinawa Trough. Ijiri et al. (2005)
335 subsequently showed the presence of a cold and less saline water mass in the northern
336 Okinawa Trough from 24 to 14 ka, based on high abundance of *Neogloboquadrina*
337 *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).

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556 Figure captions

557

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

563

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

568

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

570

571 Fig. 4. Variations in TEX_{86}-, TEX_{86}^{H}-, and TEX_{86}^{L}-derived thermocline temperature, $U_{37}^{K'}$
572 -derived SST (Ijiri et al., 2005), and *Globigerinoides ruber* Mg/Ca-derived SST (Kubota et al.,
573 2010) for the last 42 kyr from core MD98-2195. H0 = the Younger Dryas period, H1 = the
574 Oldest Dryas period. H2 = Heinrich event 2. H3 = Heinrich event 3. H4 = Heinrich event 4.

575

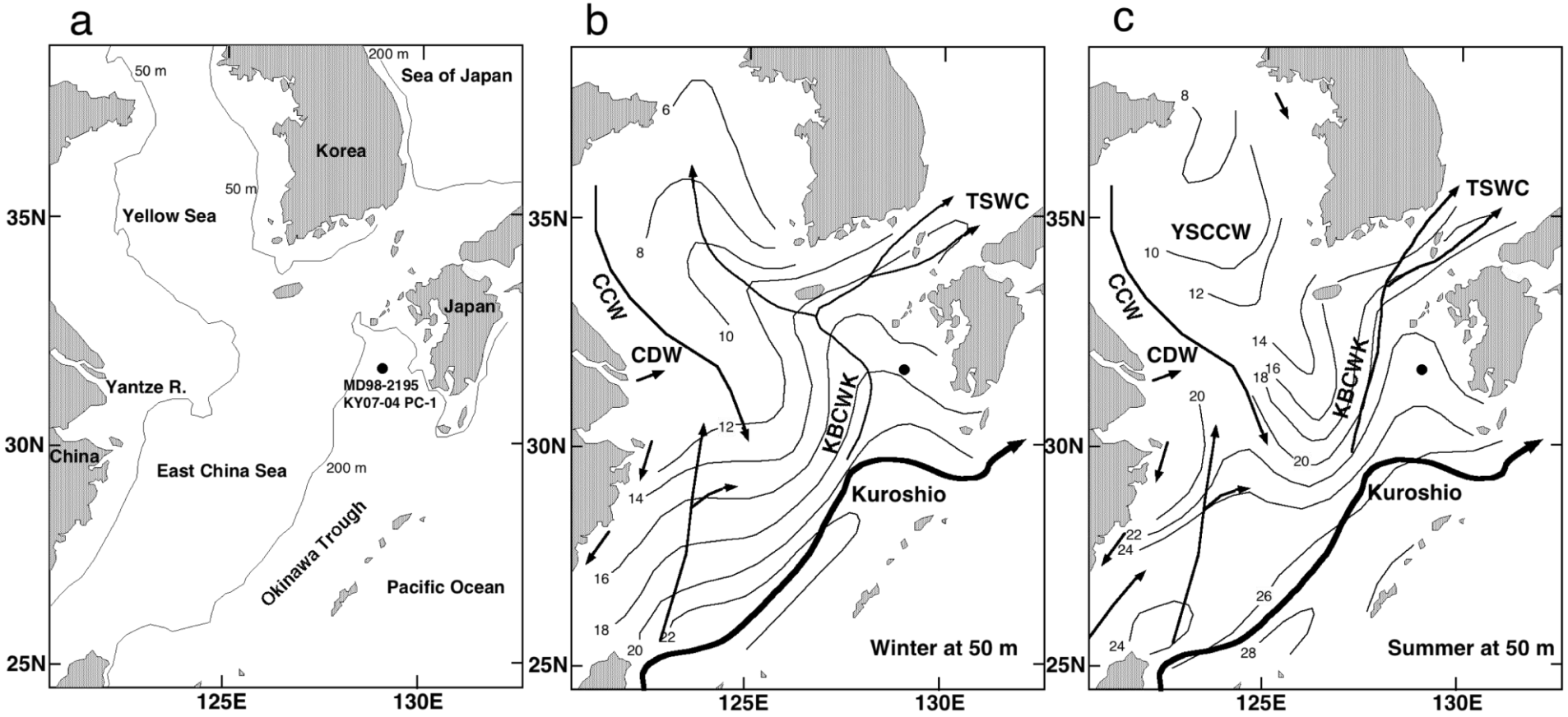
576 Fig. 5. Variation in branched and isoprenoid tetraethers (BIT) index for the last 42 kyr from
577 core MD98-2195.

578

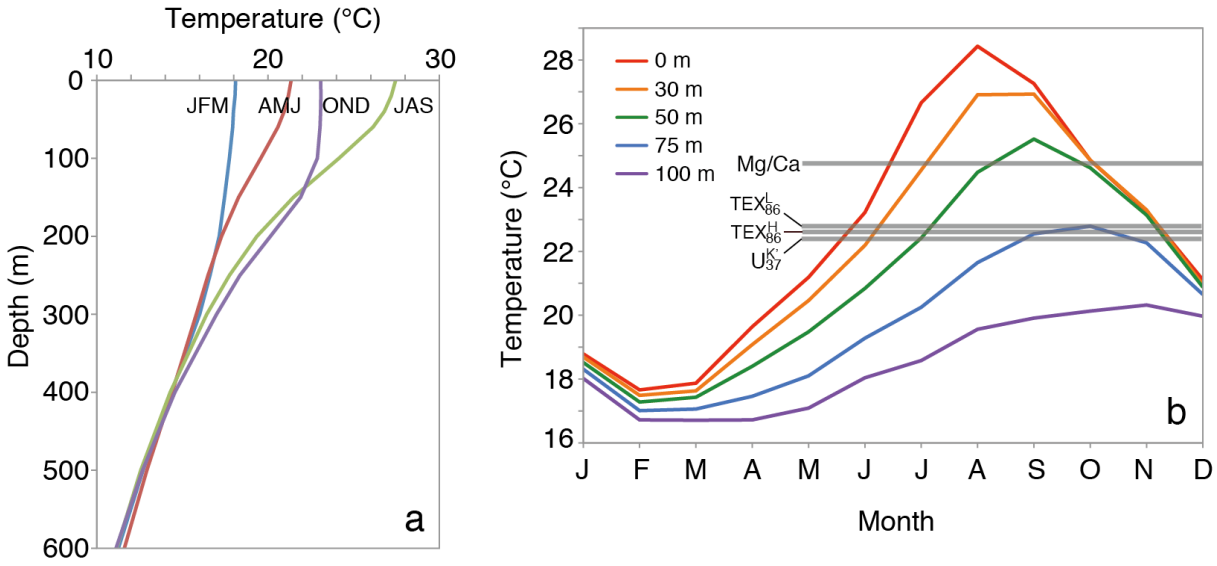
579 Fig. 6. Schematic map showing the distributions of coastline and shallow shelf area in the East
580 China Sea at 15 ka. The sea level was 100 m lower than the present. The cold water was
581 presumably formed near the study site and expanded to the northern Okinawa Trough.

582

583

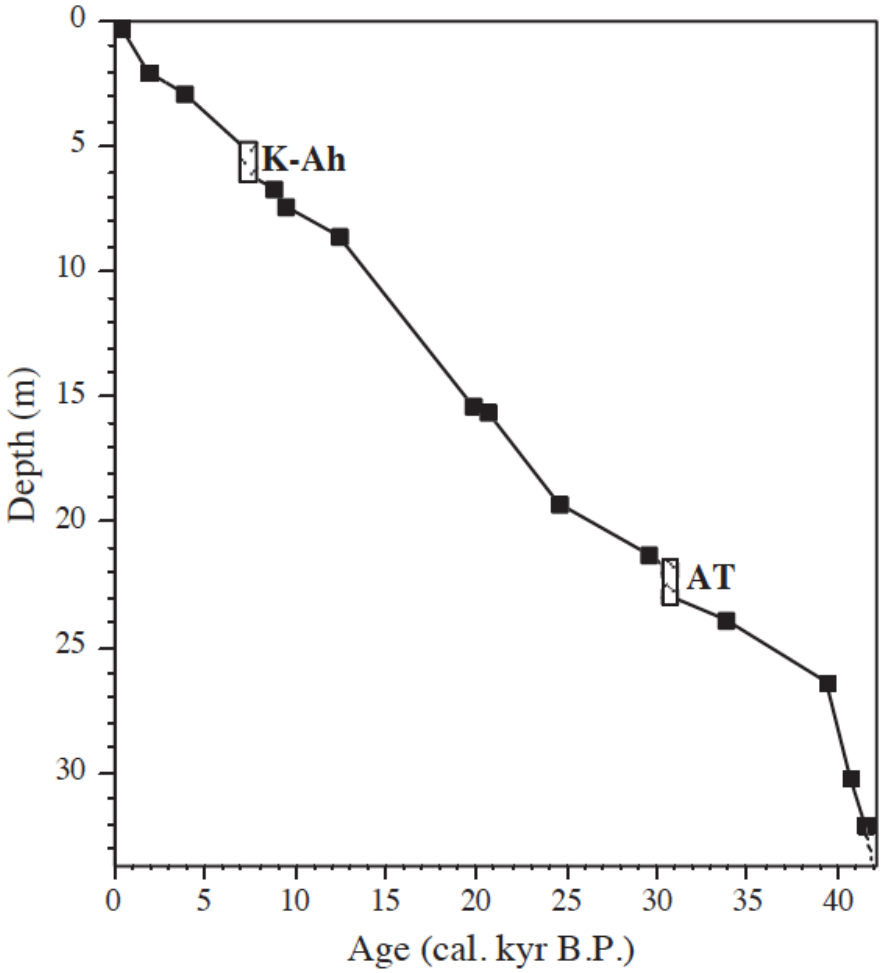

a
b
c
50 m
200 m
Sea of Japan
Korea
Yellow Sea
Japan
Yantze R.
China
East China Sea
Okinawa Trough
Pacific Ocean
MD98-2195
KY07-04 PC-1
35N
30N
25N
125E
130E
CCW
CDW
TSWC
KBCWK
Kuroshio
YSCCW
Winter at 50 m
Summer at 50 m

585 Fig. 1.



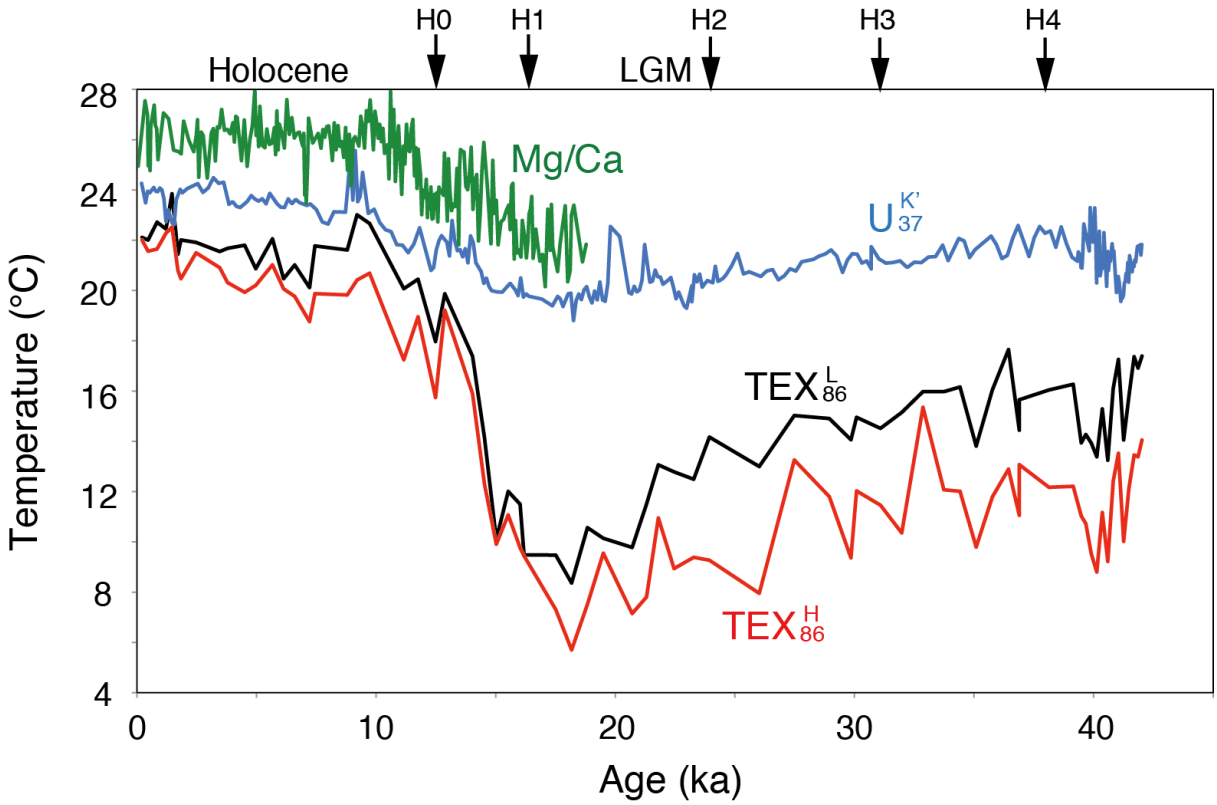
586

587 Fig. 2



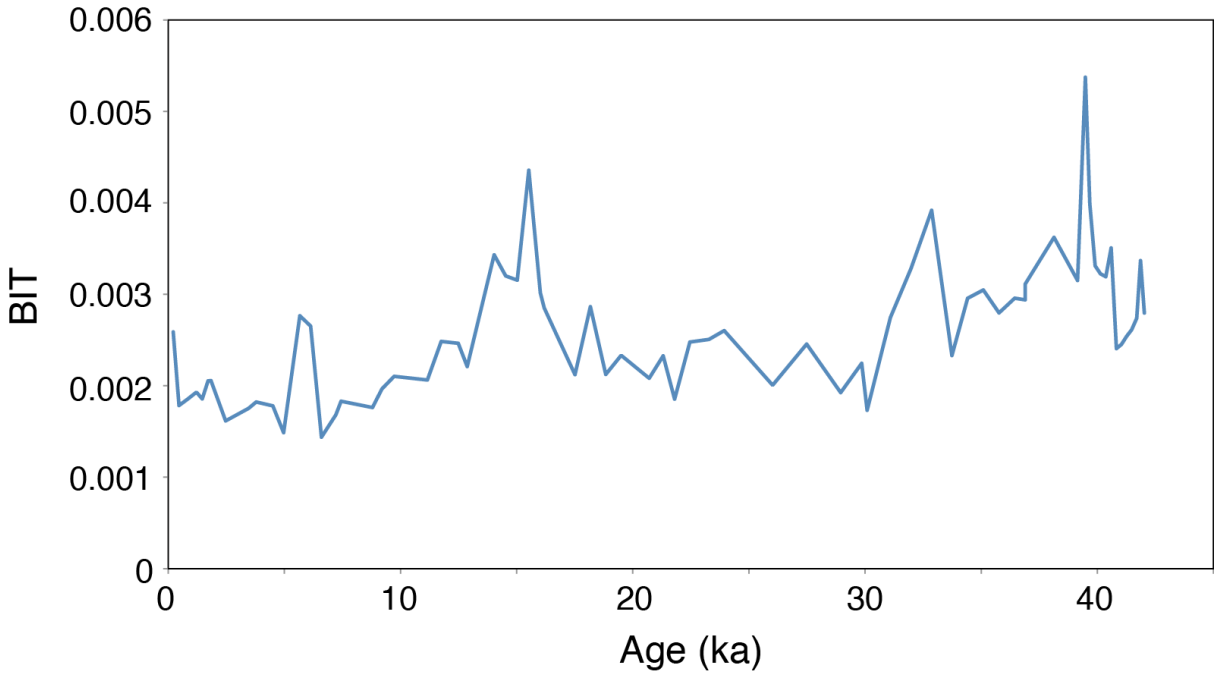
588

589 Fig. 3.



590

591 Fig. 4.



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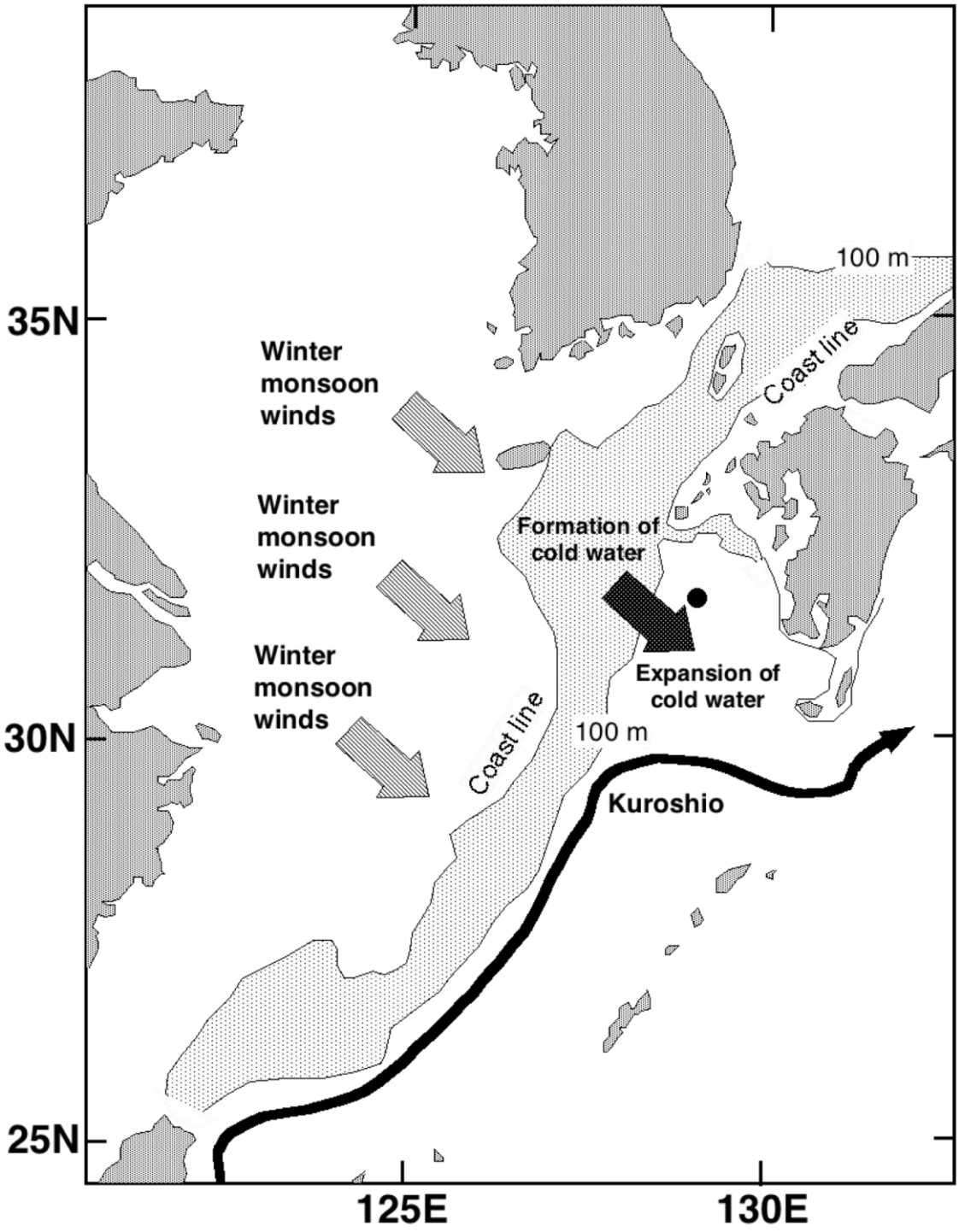
593 Fig. 5.

594


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

595

596 Fig. 6