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Changes in surface water masses in the northern East China Sea since the Last Glacial Maximum based on diatom assemblages

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Abstract

We investigated diatom assemblages for the last 19 ka in a piston core KY07-04 PC01 collected from the northern Okinawa Trough, East China Sea. Most of the diatom taxa in the Core KY07-04 PC01 were subtropical to temperate marine species throughout the core. Pronounced turnover of major diatom groups from periphytic to planktonic taxa occurred during deglaciation between 17 and 14 ka ago. During the Last Glacial Maximum (LGM) to early deglaciation, the representative taxa were *Paralia* spp., a periphytic diatom abundant in continental shelves of the modern East China Sea covering the Chinese Coastal Water. Relative abundances of *Paralia* spp. rapidly decreased during 15–14 ka ago, corresponding to sea-level rise, displaced by planktonic taxa such as *Thalassionema*. *Thalassionema nitzschioides* varieties living in subtropical water increased since 12 ka and have reached the present level at 8 ka ago, suggesting strengthening the influences of Kuroshio water in the northern East China Sea during the early to middle Holocene. Warm planktonic diatom taxa such as *Nitzschia bicipitata* also gradually increased from 12 to 8 ka ago. Near the core top, a sudden increase in *N. bicipitata* might relate to the intensifying Kuroshio during the latest Holocene.

Keywords: Diatoms, East China Sea, Sediment core, Last Glacial Maximum, Holocene, Water mass, Chinese coastal water, Kuroshio

1 Introduction

The East China Sea is a marginal sea of the western North Pacific bordered by the Kyushu, the Ryukyu Islands, and Taiwan. The East China Sea connects with the Japan Sea via the Tsushima Strait (~130 m sill depth) and the South China Sea via the Taiwan Strait (less than 100 m in depths). The East China Sea is composed of two areas: continental shelves (<200 m water depth) in the north-west, including the Yellow Sea, and the Okinawa Trough (1000–2200 m water depth) in the southeast (Fig. 1). The Yellow River (Huanghe) and the Yangtze River

(Changjiang) discharge into the East China Sea, providing much fresh water and suspended particles. The Yellow River is the second largest river globally in suspended sediment load (Milliman and Meade 1983). The Yangtze River supplies about 80% of the total discharge of freshwater from rivers flowing into the East China Sea, playing a critical role in sea-surface salinity distribution of the continental shelves of the East China Sea (Ichikawa and Beardsley 2002).

Bathymetry constrains the distribution of surface water masses and oceanic fronts in the East China Sea (Ichikawa and Beardsley 2002). The Kuroshio is a western boundary current of the North Pacific, playing an essential role in poleward heat transport (Qiu 2019). The Kuroshio flows northward and enters the East China Sea through the channel between Taiwan and Yonaguni-Jima. In the East China Sea, the Kuroshio path follows closely

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along the steep continental slope and changes the direction to the east around $\sim 30^{\circ}\text{N}$, flowing out to the Philippine Sea through the Tokara Strait. As a result, warm, saline, and nutrient-depleted Kuroshio water occupies the southern and central Okinawa Trough. The Tsushima Warm Current flows northward and enters the Japan Sea through the Tsushima Strait. The Taiwan Warm Current flowing northward through the Taiwan Strait and onshore Kuroshio intrusion across the East China Sea shelf break is the source of the Tsushima Warm Current (Isobe 2008). This warm water prevails in the northern Okinawa Trough. The Chinese Coastal Current flows southward along the Chinese coast on the continental shelves of the western East China Sea, mixing the Yangtze River discharge (Ichikawa and Beardsley 2002). Thus, cold, less saline, and nutrient-rich Chinese Coastal water distributes in the continental shelf regions of the East China Sea.

The East China Sea has experienced marked geographic changes with the sea-level rise since the LGM. During the LGM between 21 and 17 ka ago, sea-level was estimated to be -125 to -130 m (Yokoyama et al. 2018), leading to aerial exposure of most East China Sea continental shelves, closure of the Taiwan Strait, and constriction of the Tsushima Strait. Such major geographic changes must have led to changes in the distribution and circulation of surface water in the East China Sea. There is a line of evidence for low sea-surface temperature (SST) widely observed over the glacial East China Sea (Ijiri et al. 2005; Sun et al. 2005; Chang et al. 2009a; Yu et al. 2009; Chen et al. 2010; Kubota et al. 2010, 2015b; Xu et al. 2013; Ujiie et al. 2016; Matsuzaki et al. 2019), expansion of the Chinese Coastal Water (Xu and Oda 1999), advancement of river mouths of the Yellow River (Xu et al. 2014; Zheng et al. 2016; Zhao et al. 2017, 2018; Beny et al. 2018) and the Yangtze River (Dou et al. 2010a, b, 2012). Most previous studies indicated weakened the Kuroshio Current during the LGM. At the same time, Kawahata and Ohshima (2004) suggested an intrusion of the Kuroshio Current into the northern East China Sea during the LGM based on the occurrence of pollen *Phyllocladus*, celery pines originated in New Guinea and Southeast Asia. The glacial path is controversial as reviewed by Gallagher et al. (2015) whether the southward migration occurred (Ujiie et al. 2003; Su and Wei 2005; Kao et al. 2006; Dou et al. 2010a, b, 2012, 2016; Lim et al. 2017; Li

et al. 2018; Ma et al. 2021) or the path remained similar to the modern position (Lee et al. 2013; Zheng et al. 2016; Vogt-Vincent and Mitarai 2020).

Diatoms are unicellular photosynthetic eukaryotes producing biogenic opal frustules found in nearly all marine and freshwater habitats. They are one of the most major primary producers playing essential roles in the carbon and silicon cycles of the ocean (Smol and Stoermer 2010). A great diversity of species is living by sensitively responding to the aquatic environmental changes. In the modern East China Sea, characteristic diatom assemblages are dwelling in response to the water masses changes and the with pronounced seasonality (Asaoka 1975, 1980; Oh and Koh 1995; Furuya et al. 1996; Chiang et al. 1999; Ishikawa and Furuya 2004; Guo et al. 2014; Li et al. 2014; Chen et al. 2019b). Although the East China Sea is befitting for reconstructing changes in surface water masses, a few paleoceanographic studies employing diatom assemblages are available. Chang et al. (2009b) presented a diatom assemblage record in Core MD01-2404 from the central part of the Okinawa Trough for the past 100 ka at millennial timescales. The diatom record in Core MD01-2404 seemed to be synchronous with the millennial-scale climate changes in the high-latitude Northern Hemisphere during the glacial-deglacial periods. Tanimura et al. (2002) employed a periphytic diatom, *Paralia sulcata*, in Core KH82-4 St-14 from the northern Okinawa Trough to discuss the expansion and retreat of the Chinese Coastal Water since the LGM with centennial timescales. They found abundant *Paralia sulcata* during the LGM to early glacial termination, which suggested significant expansion of the Chinese Coastal Water during then. Li et al. (2012, 2015) investigated diatom assemblages in Core MD05-2908 from the southern Okinawa Trough at decadal resolutions for the past six ka. These studies have revealed that diatom assemblages are helpful to reconstruct past surface environmental changes of the East China Sea. However, a high-resolution whole assemblage record since the LGM has not yet been available in the East China Sea. Unfortunately, these previous studies (both modern and paleo) presented minimal taxonomic information and photos using a light microscope (LM). Only Li et al. (2014) presented scanning electron microscope (SEM) images for several *Thalassiosira* taxa.

(See figure on next page.)

Fig. 1 **a** Bathymetric map showing the location of Core KY07-04 PC01, MD98-2195 (yellow star), A7, and DGKS9604 (yellow circle) in the East China Sea. Dotted lines indicate 100 m water depth. Surface water masses (Kuroshio, Chinese coastal water, Changjiang River Diluted Water (CRDW), and Tsushima Warm Current (TSWC)) are shown. **b** Lower panels show the annual mean of sea-surface temperature (SST) and **c** sea-surface salinity (SSS) based on the World Ocean Atlas 2018 (Locarnini et al. 2018; Zweng et al. 2018)

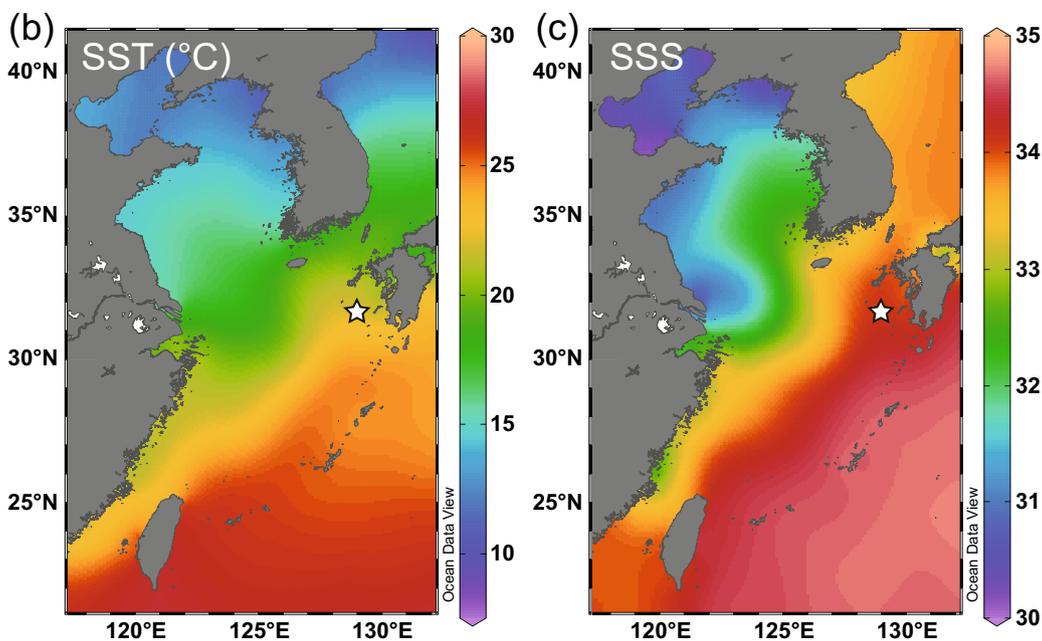
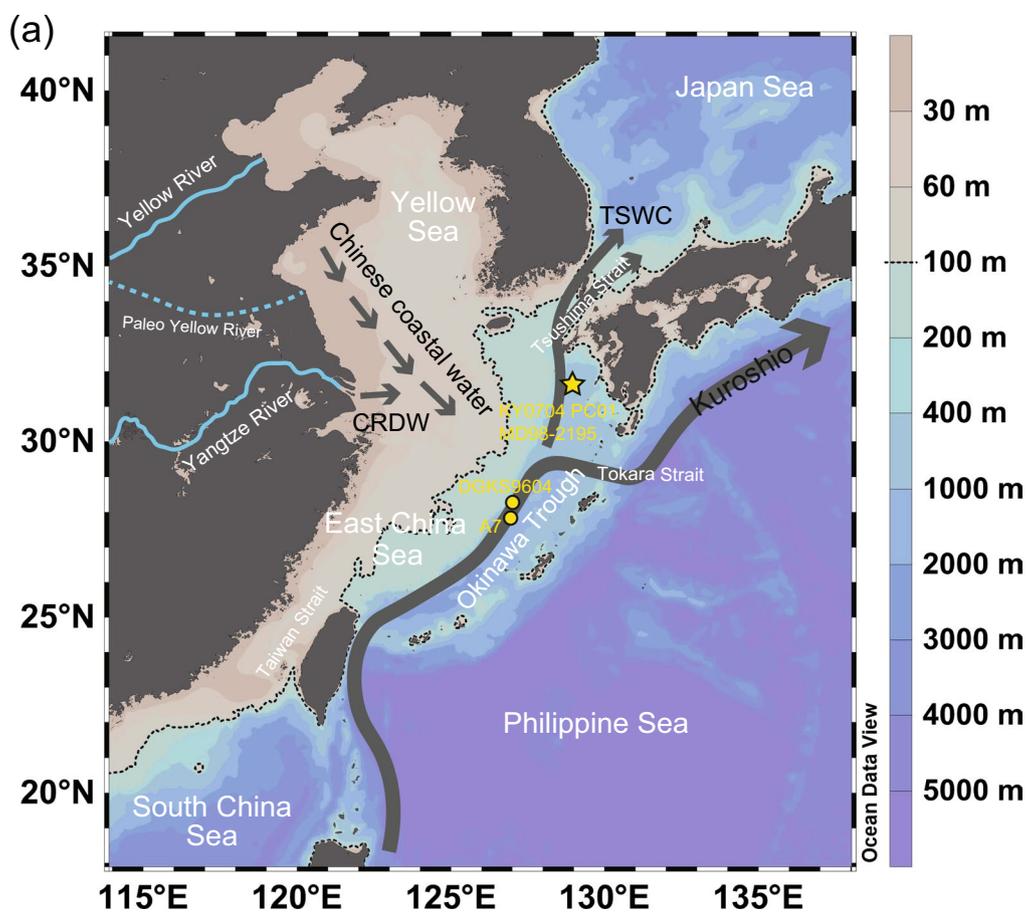


Fig. 1 (See legend on previous page.)

We present the whole diatom assemblages record and their LM and SEM images in Core KY07-04 PC01 from the northern Okinawa Trough since the LGM at centennial timescales. Available high-resolution geochemical proxy records such as oxygen isotopes and Mg/Ca SST in Core KY07-04 PC01 allow us to directly compare the diatom assemblage and the geochemical dataset (Kubota et al. 2010, 2015b). The purpose of this study is to clarify changes in surface water masses such as the Kuroshio Current and the Chinese Coastal Water from the semi-closed LGM to the present via deglacial sea-level rise.

2 Materials and methods

2.1 Core KY07-04 PC01 and its age model

A piston core sample KY07-04 PC01 was obtained from a water depth of 758 m on the northern slope of the Okinawa Trough, East China Sea (31° 38.35' N, 128° 56.64' E) during the R/V Kaiyo KY07-04 cruise in February 2007 (Fig. 1). Core KY07-04 PC01 consists of homogeneous olive to gray silty clay with two ash layers

(Kubota et al. 2010). The widespread tephra identified the upper ash layer between 408.5 and 488.5 cm in core depth as the Kikai-Akahoya (K-Ah; erupted at 7.3 ka ago).

The age model of KY07-04 PC01 was established based on 18 radiocarbon dating of planktic foraminiferal shells and tephrochronology by Kubota et al. (2010). This study revised the Core KY07-04 PC01 age model with 26 radiocarbon dating of planktic foraminiferal shells (Table 1). New radiocarbon dates for eight samples during the middle to late Holocene interval were measured by the National Electrostatics Corporation 250 kV single-stage accelerator mass spectrometry at Atmosphere and Ocean Research Institute, The University of Tokyo (Yokoyama et al. 2019). We conducted radiocarbon calibration to convert radiocarbon age to calendar age using CALIB 8.2 (Stuiver et al. 2021) with the Marine20 calibration curve (Heaton et al. 2020). Local marine reservoir age (ΔR) was estimated as -200 ± 100 yr from 33 data from the East China Sea coast (Konishi et al. 1982; Kong and Lee 2005; Hideshima et al. 2001; Southon et al. 2002; Yoneda et al.

Table 1 Age control points of Core KY07-04 PC01 by radiocarbon ages of planktic foraminifera and K-Ah tephra chronology

Core depth (cm)	^{14}C age (yr BP)	Error (yr)	Calendar age (yr BP)	Error (yr, $\pm 2\sigma$)	Foraminiferal species
2.5–12.5	185	75	Bomb ^{14}C	Bomb ^{14}C	<i>N.dutertrei</i>
2.5–12.5	265	115	Bomb ^{14}C	Bomb ^{14}C	<i>G.bulloides</i>
50–60	1040	50	670	226	<i>N.dutertrei</i>
78–79.75	1643	49	1236	266	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
98.5–103.5	2955	80	2793	357	<i>N.dutertrei</i>
102.25–104.75	2429	53	2142	320	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
124.75–127.25	2812	48	2610	293	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
151–156	2955	50	2796	321	<i>N.dutertrei</i>
173.5–176	3331	37	3239	299	<i>N. dutertrei</i>
201–206	3635	50	3637	309	<i>N.dutertrei</i>
223.5–226	4147	89	4292	391	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
251–256	4550	80	4822	376	<i>N.dutertrei</i>
273.5–276	4985	53	5313	304	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
300–302.5	5325	55	5716	279	<i>N.dutertrei</i>
322.5–325	5878	44	6304	285	<i>G. sacculifer</i> , <i>P. obliquiloculata</i> , <i>N. dutertrei</i>
365–367.5	6688	65	7180	280	<i>G. sacculifer</i> , <i>N. dutertrei</i>
409			7252	56	K-Ah tephra top
489			7252	56	K-Ah tephra bottom
492–494.5	6960	60	7452	251	<i>N.dutertrei</i>
492–502	7000	90	7502	286	<i>G.bulloides</i>
639.5–642	9040	75	9841	338	<i>N.dutertrei</i>
781–783.5	10,475	145	11,856	559	<i>N.dutertrei</i>
925.5–935.5	11,500	70	13,016	270	<i>N.dutertrei</i>
925.5–935.5	11,700	80	13,214	300	<i>G.bulloides</i>
1068.5–1071	13,250	105	15,371	428	<i>N.dutertrei</i>
1240–1247.5	14,740	80	17,295	398	<i>N.dutertrei</i>
1403.5–1408.5	15,745	105	18,434	344	<i>N.dutertrei</i>
1398.5–1408.5	15,975	105	18,637	378	<i>G.bulloides</i>

2007; Hirabayashi et al. 2017)) in 14CHRONO Marine20 reservoir correction database. The K-Ah tephra age was 7252 ± 56 yr, estimated from Lake Suigetsu varve sediment (McLean et al. 2018). Based on the radiocarbon and K-Ah tephra dates, the revised age model of Core KY07-04 PC01 was established (Table 1; Fig. 2). The revised age model is consistent with the previous one by Kubota et al. (2010). Its continuous sedimentation with a high sedimentation rate of ~ 80 cm kyr⁻¹ ensures Core KY07-04 PC01 for centennial to millennial scales paleoceanographic study.

2.2 Microscopic observation for diatoms

Core KY07-04 PC01 samples were sliced at 2.5 cm intervals and stored in a refrigerator. A total of 72 subsamples taken at ~ 20 cm intervals were taken for diatom assemblage work and freeze-dried with an EYELA FDU-1200 freeze-dryer. Approximately 1 mg of the freeze-dried sample was treated with 25 mL of 30% hydrogen peroxide at hydrogen peroxide on a hot plate with top plate temperature set to 100 °C for about 1 h to digest organic matter. After the reaction was complete, Millipore-Elix water was added to a total volume of 200 mL and allowed to stand for 8 h. The removal of supernatant was removed, and Millipore-Elix water was added again. The following is a procedure of slides for LM observation. The pretreated suspended solution of each sediment sample was drawn by 2 mL plastic pipette, dropped on cover glass (24 × 40 mm), and dried on a hot plate with top plate temperature set to 40–50 °C. Pleurax (Mount

Media, Wako Pure Chemical Industries, Tokyo, Japan) was dropped on the cover glass and mounted on the glass slide at 120 °C. LM observations were performed at magnifications of × 1000 using Olympus BX53 and BX50 bright-field microscopes to identify and count diatoms in Core KY07-04 PC01 samples. Counting of diatom valves was performed as follows: (1) for centric diatoms, a valve with a central part was counted as one valve; and (2) for pennate diatoms, a valve with an apical part was counted as 0.5 valves. More than 200 diatom valves were counted for diatom assemblage analyses of Core KY07-04 PC01 samples (Additional file 1: Tables S1 and S2).

Sample preparation for SEM observation is described as follows. The pretreated suspended solution of each sediment sample was filtered through an Advantec membrane filter (0.45 μm pore size, 47 mm diameter), rinsed with Millipore-Elix water, and dried. The filter samples were cut into 6 mm × 6 mm squares, mounted onto brass stubs with carbon tape, and coated with OsO₄ using an osmium coater (Neoc-STB; Meiwafoods Co. Ltd., Tokyo, Japan). A field-emission scanning electron microscope (FE-SEM, JMS-7001F; JEOL Ltd., Akishima, Japan) was used for detailed taxonomic work of the diatoms. The acceleration voltage was set at 5 kV.

Identification and counting were conducted at the species level as much as possible. Images of observed major diatom taxa are shown in Additional file 2: Plates 1–6 in the supplement. We counted specimens belonging to the genus *Paralia* as *Paralia* spp. *Paralia* spp. include several species such as *P. sulcata*, *P. fenestrata*, *P. longispina*, *P. allisonii*, *P. crawfordii*, *P. ehrmanii*, and *P. obscura* (Hasle and Syvertsen 1997; Sawai et al. 2005; Konno and Jordan 2008; MacGillivray and Kaczmarek 2012, 2013). The morphology of encountered *Paralia* specimens in Core KY07-04 PC01 often had intermediate features between the species and was hard to identify by LM observation. Genus *Thalassionema* was one of the most abundant diatoms in Core KY07-04 PC01 samples. This study classified *Thalassionema* into six species, four varieties, and two morphological types (Table 2; Additional file 2: Plate 4–6) following to Hasle and Syvertsen (1997), Tanimura (1999), Hasle (2001), Tanimura et al. (2007) and Akiba et al. (2014). The diatom taxa were grouped by their lifestyle (periphytic, planktonic), habitats (freshwater, brackish, marine), and geographic distributions (coastal, cold, warm) based on Round et al. (1990), Hasle and Syvertsen (1997), and Koizumi (2008) (Table 2).

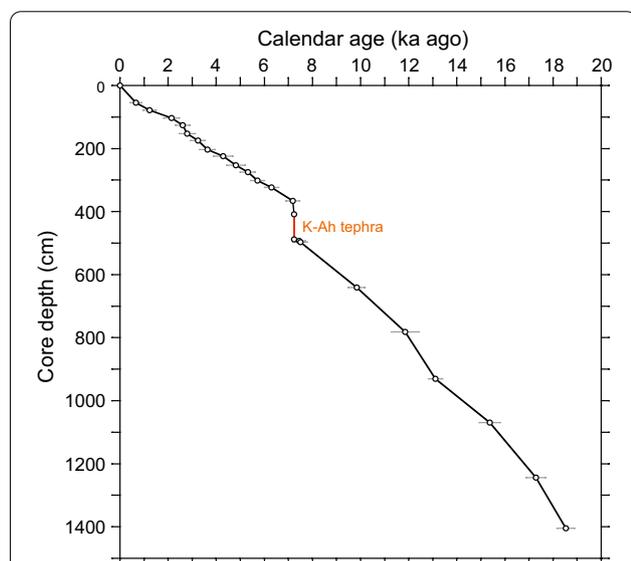


Fig. 2 The age–depth plot of Core KY07-04 PC01. Open circles denote radiocarbon dates (calibrated to calendar age) of planktic foraminifera with error bars ($\pm 1\sigma$). Orange vertical line indicates K-Ah tephra stratum. The K-Ah tephra datum (7252 ± 56 yr ago) is from Lake Suigetsu varve sediment (McLean et al. 2018)

3 Results

One hundred twenty-five diatom taxa were observed in Core KY07-04 PC01 samples (Table 2). *Paralia*, *Thalassionema*, and *Nitzschia* were the most abundant diatom genus in Core KY07-04 PC01 samples (Fig. 3). *Paralia*

Table 2 Diatom taxa identified in Core KY07-04 PC01 with their ecological distributions

Diatom taxa	Categories
<i>Achnanthes</i> spp.	Periphytic
<i>Actinocyclus</i> cf. <i>oconarius</i> Ehrenberg	Marine, Coastal
<i>Actinocyclus</i> spp.	Marine, Coastal
<i>Actinoptychus senarius</i> (Ehrenberg) Ehrenberg	Marine, Coastal
<i>Actinoptychus</i> cf. <i>splendens</i> (Shadbolt) Ralfs	Marine, Coastal
<i>Actinoptychus</i> spp.	Marine, Coastal
<i>Alveus marinus</i> (Grunow) Kaczmarek and Fryxell	Planktonic, Marine, Warm
<i>Amphora</i> spp.	Periphytic
<i>Ardissonea</i> cf. <i>robusta</i> (Ralfs ex Pritchard) De Notaris	Periphytic, Brackish/Marine, Coastal
<i>Asterolampira</i> sp.	Planktonic, Marine, Warm
<i>Asteromphalus arachne</i> (Brébisson) Ralfs	Planktonic, Marine, Warm
<i>Asteromphalus flabellatus</i> (Brébisson) Greville	Planktonic, Marine, Warm
<i>Asteromphalus</i> sp.	Planktonic, Marine, Warm
<i>Aulacoseira</i> spp.	Planktonic, Freshwater
<i>Azpeitia nodulifera</i> (Schmidt) Fryxell and Sims	Planktonic, Marine, Warm
<i>Azpeitia</i> spp.	Planktonic, Marine
<i>Bacillaria</i> spp.	Periphytic
<i>Bacteriastrum</i> cf. <i>delicatulum</i> Cleve	Planktonic, Marine
<i>Bacteriastrum</i> cf. <i>hyalinum</i> Lauder	Planktonic, Marine
<i>Bacteriastrum</i> spp.	Planktonic, Marine
<i>Biddulphia</i> spp.	Marine, Coastal
<i>Campylosira</i> sp.	Periphytic, Marine, Coastal
<i>Catenula</i> cf. <i>adhaerens</i> (Mereschkowsky) Mereschkowsky	Periphytic, Marine, Coastal
<i>Chaetoceros</i> spp.	Planktonic, Marine
<i>Climacodium frauenfeldianum</i> Grunow	Planktonic, Marine, Warm
<i>Cocconeis scutellum</i> Ehrenberg	Periphytic, Marine, Coastal
<i>Cocconeis</i> spp.	Periphytic
<i>Coscinodiscus marginatus</i> Ehrenberg	Planktonic, Marine, Cold
<i>Coscinodiscus radiatus</i> Ehrenberg	Planktonic, Marine
<i>Coscinodiscus</i> spp.	Planktonic, Marine
<i>Cyclostephanos</i> spp.	Planktonic, Freshwater
<i>Cyclotella choctawhatcheeana</i> Prasad	Planktonic, Brackish/Marine, Coastal
<i>Cyclotella litoralis</i> Lange and Syvertsen	Planktonic, Brackish/Marine, Coastal
<i>Cyclotella striata</i> (Kützing) Grunow	Planktonic, Brackish/Marine, Coastal
<i>Cyclotella stylorum</i> Brightwell	Planktonic, Brackish/Marine, Coastal, Warm
<i>Cyclotella</i> spp.	Planktonic, Coastal
<i>Cymatosira lorenziana</i> Grunow	Periphytic, Marine, Coastal, Warm
<i>Cymatosira</i> spp.	Periphytic, Marine, Coastal
<i>Cymatotheca</i> spp.	Marine
<i>Cymbella</i> spp.	Periphytic, Freshwater
<i>Delphineis australis</i> (Petit) Watanabe, Tanaka, Reid, Kumada and Nagumo	Periphytic, Marine, Coastal
<i>Delphineis minutissima</i> (Hustedt) Simonsen	Periphytic, Marine, Coastal
<i>Delphineis surirella</i> (Ehrenberg) Andrews	Periphytic, Marine, Coastal
<i>Delphineis</i> spp.	Periphytic, Marine, Coastal
<i>Denticula antillarum</i> Cleve	Periphytic, Coastal
<i>Diatoma</i> spp.	Periphytic, Freshwater
<i>Dimeregramma</i> spp.	Marine, Coastal
<i>Diploneis</i> cf. <i>crabro</i> (Ehrenberg) Ehrenberg	Periphytic, Marine, Coastal
<i>Diploneis</i> cf. <i>suborbicularis</i> (Gregory) Cleve	Periphytic, Marine, Coastal

Table 2 (continued)

Diatom taxa	Categories
<i>Diploneis</i> spp.	Periphytic, Coastal
<i>Discostella</i> sp.	Planktonic, Freshwater
<i>Ditylum brightwellii</i> (West) Grunow	Planktonic, Marine, Coastal
<i>Eucampia</i> spp.	Planktonic, Marine
<i>Eunotia</i> spp.	Periphytic, Freshwater
<i>Fallacia</i> spp.	Periphytic
<i>Fragilaria</i> spp.	Periphytic, Freshwater
<i>Fragilariopsis doliolus</i> (Wallich) Medlin and Sims	Planktonic, Marine, Warm
<i>Glyphodesmis</i> spp.	Periphytic, Marine, Coastal
<i>Grammatophora</i> spp.	Periphytic, Marine, Coastal
<i>Gyrosigma</i> spp.	Periphytic, Brackish/Marine, Coastal
<i>Hemiaulus</i> sp.	Planktonic, Marine
<i>Hemidiscus</i> cf. <i>cuneiformis</i> Wallich	Planktonic, Marine, Warm
<i>Hyalodiscus</i> spp.	Periphytic, Marine, Coastal
<i>Hydrosera</i> spp.	Periphytic, Brackish/Marine, Coastal
<i>Lioloma</i> spp.	Planktonic, Marine
<i>Lyrella</i> spp.	Periphytic, Marine, Coastal
<i>Mastogloia</i> sp.	Periphytic
<i>Melosira</i> sp.	Periphytic
<i>Minidiscus</i> spp.	Planktonic, Marine, Coastal
<i>Navicula</i> spp.	Periphytic
<i>Neodelphineis indica</i> (Taylor) Tanimura	Planktonic, Marine, Warm
<i>Neodelphineis pelagica</i> Takano	Planktonic, Marine, Warm
<i>Nitzschia bicapitata</i> Cleve	Planktonic, Marine, Warm
<i>Nitzschia capuluspalae</i> Simonsen	Planktonic, Marine, Warm
<i>Nitzschia interruptestriata</i> Simonsen	Planktonic, Marine, Warm
<i>Nitzschia</i> cf. <i>sicula</i> (Castracane) Hustedt	Planktonic, Marine, Warm
<i>Nitzschia</i> spp.	Planktonic
<i>Odontella</i> spp.	Planktonic, Marine
<i>Opephora</i> spp.	Periphytic, Marine, Coastal
<i>Paralia</i> cf. <i>sulcata</i> (Ehrenberg) Cleve	Periphytic, Marine, Coastal
<i>Paralia</i> spp.	Periphytic, Marine, Coastal
<i>Plagiogramma</i> spp.	Periphytic, Marine, Coastal
<i>Plagiogrammopsis</i> cf. <i>vanheurckii</i> (Grunow) Hasle, Stosch and Syvertsen	Periphytic, Marine, Coastal
<i>Pleurosigma</i> spp.	
<i>Porosira</i> spp.	Planktonic, Marine
<i>Proboscia</i> spp.	Planktonic, Marine
<i>Psammodictyon panduriforme</i> (Gregory) Mann	Periphytic, Marine, Coastal
<i>Psammodictyon</i> spp.	Periphytic, Marine, Coastal
<i>Pseudotriceratium</i> spp.	Planktonic, Marine
<i>Rhaphoneis</i> spp.	Periphytic, Marine, Coastal
<i>Rhizosolenia bergonii</i> Peragallo	Planktonic, Marine, Warm
<i>Rhizosolenia setigera</i> Brightwell	Planktonic, Marine
<i>Rhizosolenia styliformis</i> Brightwell	Planktonic, Marine
<i>Rhizosolenia</i> spp.	Planktonic, Marine
<i>Rhopalodia</i> sp.	Periphytic
<i>Roperia tessellata</i> (Roper) Grunow ex Pelletan	Planktonic, Marine
<i>Shionodiscus oestrupii</i> (Ostenfeld) Alverson, Kang and Theriot	Planktonic, Marine, Warm
<i>Shionodiscus trifultus</i> (Fryxell) Alverson, Kang and Theriot	Planktonic, Marine, Cold

Table 2 (continued)

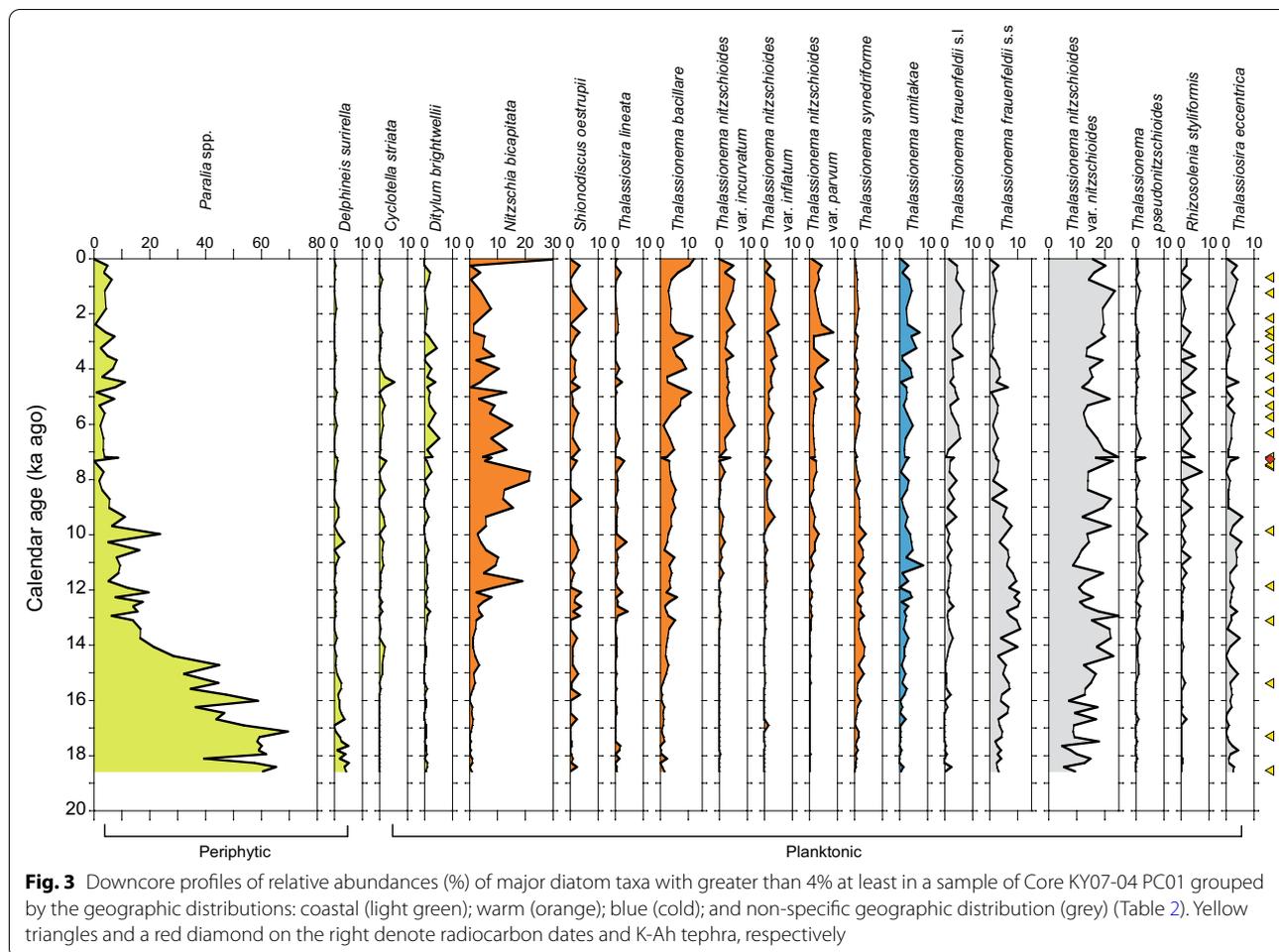
Diatom taxa	Categories
<i>Shionodiscus</i> spp.	Planktonic, Marine
<i>Skeletonema</i> sp.	Planktonic, Marine, Coastal
<i>Staurosira</i> spp.	Freshwater
<i>Surirella</i> spp.	Periphytic
<i>Synedra</i> spp.	Periphytic, Freshwater
<i>Tabellaria</i> spp.	Periphytic, Freshwater
<i>Thalassionema bacillare</i> (Heiden) Kolbe	Planktonic, Marine, Warm
<i>Thalassionema frauenfeldii</i> (Grunow) Tempère and Peragallo sensu lato	Planktonic, Marine
<i>Thalassionema frauenfeldii</i> (Grunow) Tempère and Peragallo sensu stricto	Planktonic, Marine
<i>Thalassionema nitzschioides</i> (Grunow) Mereschkowsky	Planktonic, Marine
<i>Thalassionema nitzschioides</i> var. <i>incurvatum</i> Heiden	Planktonic, Marine, Warm
<i>Thalassionema nitzschioides</i> var. <i>inflatum</i> Heiden	Planktonic, Marine, Warm
<i>Thalassionema nitzschioides</i> var. <i>parvum</i> Heiden	Planktonic, Marine, Warm
<i>Thalassionema nitzschioides</i> varieties	Planktonic, Marine, Warm
<i>Thalassionema pseudonitzschioides</i> (Schuette and Schrader) Hasle	Planktonic, Marine
<i>Thalassionema synedriforme</i> (Greville) Hasle	Planktonic, Marine, Warm
<i>Thalassionema umitakae</i> Akiba et Tanimura	Planktonic, Marine, Cold
<i>Thalassionema</i> spp.	Planktonic, Marine
<i>Thalassiosira eccentrica</i> (Ehrenberg) Cleve	Planktonic, Marine
<i>Thalassiosira</i> cf. <i>leptopus</i> (Grunow) Hasle and Fryxell	Planktonic, Marine
<i>Thalassiosira lineata</i> Jousé	Planktonic, Marine, Warm
<i>Thalassiosira nordenskiöldii</i> Cleve	Planktonic, Marine, Cold
<i>Thalassiosira</i> spp.	Planktonic, Marine
<i>Thalassiothrix spathulata</i> Hasle	Planktonic, Marine, Warm
<i>Thalassiothrix</i> spp.	Planktonic, Marine
<i>Trachyneis</i> sp.	Periphytic, Marine, Coastal
<i>Tryblionella</i> spp.	Periphytic

(periphytic) was the dominant genus before 14 ka ago, whereas *Thalassionema* and *Nitzschia* (planktonic) were abundant after 14 ka ago.

At the species level, downcore profiles of diatom taxa with greater than 4% at least in a sample were shown (Fig. 3). *Paralia* spp., periphytic coastal diatom taxa, was representative in Core KY07-04 PC01 samples before 14 ka ago, exceeding 30% during the LGM and early deglaciation from 19 to 15 ka ago (Fig. 3). Another periphytic coastal diatom species, *Delphineis surirella*, showed a similar pattern with *Paralia* spp., with high relative abundances before 16 ka ago (Fig. 3). Relative abundances of *Nitzschia bicipitata*, a major planktonic warm species, were high from the deglacial period to middle Holocene and the core top of Core KY07-04 PC01 (Fig. 3). *Thalassionema* species and varieties presented various downcore profile patterns in Core KY07-04 PC01

(Fig. 3). Morphological varieties of *Thalassionema nitzschioides* were persistently high percentages throughout the core. Among the *T. nitzschioides* varieties, three varieties (var. *incurvatum*, var. *inflatum*, and var. *parvum*) increased during the middle-late Holocene. On the other hand, *Thalassionema frauenfeldii* sensu stricto (s.s.) and *Thalassionema synedriforme* were relatively high during the deglacial period.

Figure 4 shows diatom groups by habitats (freshwater and brackish) and geographic distributions (coastal, cold, warm) in Core KY07-04 PC01. During the LGM, periphytic diatoms, mostly *Paralia* spp., were predominant, whereas planktonic diatoms were the minority. During the deglacial pronounced turnover between 18 and 14 ka ago, Planktonic diatoms became the majority in Core KY07-04 PC01. With the turnover, coastal diatoms decreased significantly. Note that contributions of



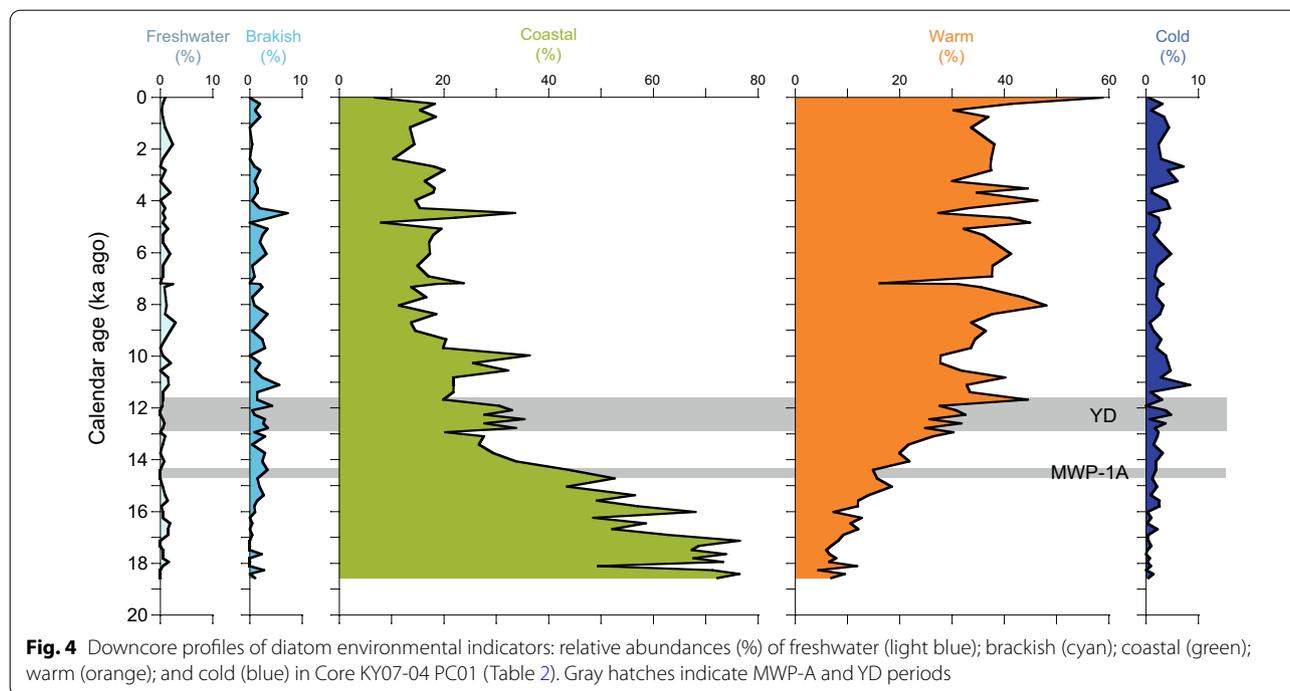
freshwater and brackish water diatoms have been small in total assemblage even during the LGM and early deglaciation (Fig. 4). Marine diatoms were the majority in the diatom assemblages in Core KY07-04 PC01 since the LGM. Planktonic warm water diatom group gradually increased from 18 to 12 ka ago, occupying ~40% for the last 12 ka.

4 Discussion

4.1 Diatom assemblages as paleoenvironmental indicators

Throughout the core, marine diatoms were dominant, suggesting that the northern Okinawa Trough has been a marine environment and limited fresh/brackish water influences even during the LGM. This is consistent with the previous study reporting the continuous occurrences of planktic foraminifera (Xu and Oda 1999; Ijiri et al. 2005) and radiolarians (Matsuzaki et al. 2019) during the LGM in the northern East China Sea. Periphytic diatom *Paralia* spp. were dominant in the Core KY0704 PC01 during the LGM. Previous studies in the modern and past East China Sea referred to as *Paralia sulcata*, equivalent

to *Paralia* spp. in the present study (Asaoka 1980; Oh and Koh 1995; Furuya et al. 1996; Tanimura et al. 2002; Chang et al. 2009b; Ishikawa and Furuya 2004; Guo et al. 2014; Yuan et al. 2014; Chen et al. 2019b). *Paralia* spp. distributes on muddy sediments of the Japanese coast with salinity ranging from 11 to 34 (Sawai et al. 2005). In the modern East China Sea and the Yellow Sea, *Paralia* spp. dwells on the continental shelves as a representative coastal water indicator throughout the year (Asaoka 1980; Furuya et al. 1996; Ishikawa and Furuya 2004; Guo et al. 2014; Yuan et al. 2014; Chen et al. 2019b), including the eutrophic coastal area of the Yellow Sea (Di et al. 2013; Liu et al. 2013). Asaoka (1980) revealed that *Paralia* spp. distributions in summer were almost synchronous with suspended mud deposited on the central part of East China Sea continental shelves. Furuya et al. (1996) and Ishikawa and Furuya (2004) reported dominant *Paralia* spp. in the inner shelf area (<70 m water depth) by active vertical mixing in winter and spring, respectively. Guo et al. (2014) presented the seasonality of diatom assemblages and the abundances in the continental shelf area



of the East China Sea. Based on their study, *Paralia* spp. was one of the most abundant diatom taxa in spring, fall, and winter. On the other hand, the occurrence of *Paralia* spp. was low in summer. These modern observations have clarified that abundant *Paralia* spp. occurrences in the nutrient-rich shelf water of the East China Sea with temperatures ranging from 11 to 20 °C and salinity from 33.5 to 34.5. This water-mass property corresponds to the water mass properties of Chinese coastal water (Ichikawa and Beardsley 2002). *Paralia* spp. is transported with suspended mud from the coastal area/continental shelves to the northeastern East China Sea.

Tanimura et al. (2002) investigated *Paralia* spp. abundances in KH82-4 St-14 piston core (31° 44.4' N, 129° 02.1' E, 740 m water depth) adjacent to KY07-04 PC01. They found abundant *Paralia* spp. occurrences from 19 to 13 cal ka BP (16–10 ka BP in ¹⁴C age shown in Tanimura et al. (2002), suggesting a significant expansion of Chinese coastal water sea-level drop during the LGM to early deglaciation. A similar but much smaller (up to 20%) abundance peak during the LGM to early deglaciation was observed at Core MD01-2404 in the southwestern Okinawa Trough (Chang et al. 2009b). *Delphineis surirella*, a periphytic coastal diatom species that dwell in the subtidal zone (Zong and Horton 1999; Sawai et al. 2009), showed relatively high abundances during 19–14 ka ago, presenting a similar pattern with *Paralia* spp. (Fig. 3). These consistently support the expansion of Chinese coastal water during the LGM to early deglaciation.

In Core KY-07-04 PC01, planktonic diatom *Thalassionema* was the dominant diatom genus since 14 ka ago (Fig. 3). This study classified *Thalassionema* into six species, four varieties, and two morphological types (Table 2; Fig. 3) following the previous studies (Hasle and Syvertsen 1997; Tanimura 1999; Hasle 2001; Tanimura et al. 2007; Akiba et al. 2014). *Thalassionema nitzschioides* is known as a cosmopolitan planktonic species (Hasle 2001). In the East China Sea, occurrences of *Thalassionema nitzschioides* have been reported from the Yellow Sea, the continental shelves, and the Okinawa Trough (Asaoka 1975, 1980; Oh and Koh 1995; Furuya et al. 1996; Chiang et al. 1999; Ishikawa and Furuya 2004; Guo et al. 2014). In particular, *Thalassionema nitzschioides* was abundant near the shelf break (Furuya et al., 1996; Chiang et al., 1999; Ishikawa and Furuya, 2004; Guo et al., 2014).

Tanimura et al. (2007) indicated that each *Thalassionema nitzschioides* species and varieties showed specific geographical distributions in the North Pacific: *T. nitzschioides* var. *nitzschioides* and *T. pseudonitzschioides* in the Subarctic Gyre; *T. nitzschioides* var. *incurvatum*, var. *inflatum*, and var. *parvum* in the Subtropical Gyre. Tanimura (1999) proposed a ratio of three *T. nitzschioides* varieties (var. *incurvatum*, var. *inflatum*, and var. *Parvum*) in *Thalassionema nitzschioides* complex (hereafter refers as T-ratio) as an index for Kuroshio intensity based on sediment trap experiments in the Kuroshio path, western North Pacific. Tanimura (1999) exhibited temporal changes in T-ratio and distance from

the Kuroshio (the shortest distance from the trap station to the Kuroshio path). When Kuroshio migrated to the north, the sediment trap station was covered with subtropical water where the three *T. nitzschioides* varieties were abundant. In Core KY-07-04 PC01, T-ratio has increased since 12 ka ago and has reached its present level since 8 ka ago (Fig. 5), which is consistent with the timings of northward migration of Kuroshio in the western North Pacific (Takemoto and Oda 1997; Tanimura 1999; Yamamoto et al. 2005) and intensification of Tsushima Warm Current flowing into the Japan Sea (Gallagher et al. 2015; Yokoyama et al. 2006), respectively. A typical dark color layer in many deep-sea sediment cores from the Japan Sea with high organic carbon contents, called TLL, is seen when the Tsushima Warm Current intrusion was re-established since the LGM (Oba et al. 1991; Tada et al. 1999; Yokoyama et al. 2006). Thus, the T-ratio

increase suggests strengthening the influence of Kuroshio Current water in the northern East China Sea.

Tanimura et al. (2007) recognized nine species, varieties, and morphological types of *Thalassionema nitzschioides*. Akiba et al. (2014) described the Nd morphological type of *Thalassionema nitzschioides* sensu lato (s.l.) as a new species *Thalassionema umitakae*. The distribution of *T. umitakae* in the North Pacific is mainly in the subarctic region but a few occurrences in the subarctic boundary of the western North Pacific (Tanimura et al. 2007). Abundant occurrences of *T. umitakae* were reported in the glacial Japan Sea (Akiba et al. 2014). In Core KY07-04 PC01, *T. umitakae* occurred throughout the core since the LGM with no pronounced trend (Fig. 3), implying no significantly cold surface water covered in the northern Okinawa Trough even during the LGM.

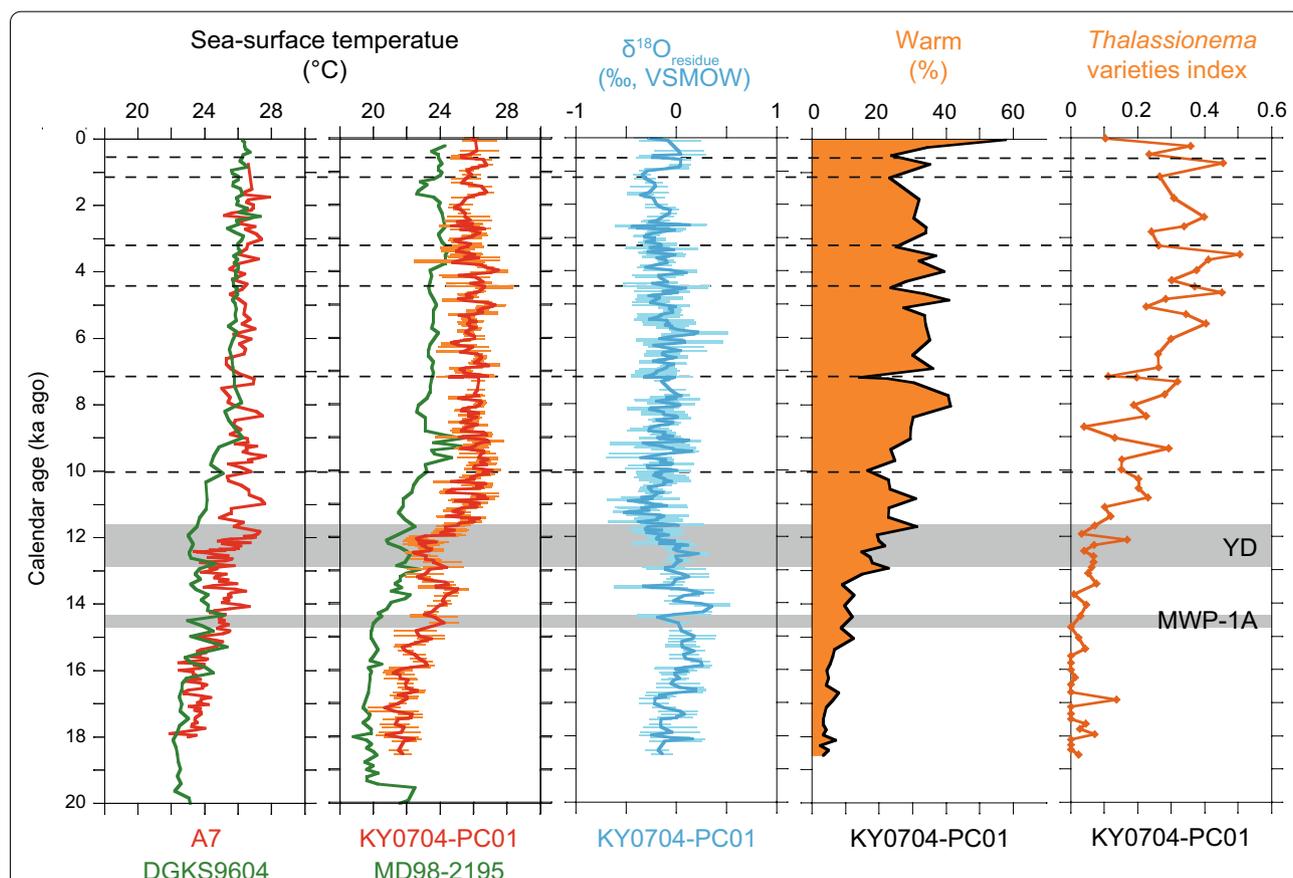


Fig. 5 Sea-surface temperature records based on planktic foraminiferal Mg/Ca (red) and alkenones in the central Okinawa Trough: Core A7 (Sun et al. 2005) and Core DGKS9604 (Yu et al. 2009); and the northern Okinawa Trough: Core KY07-04 PC01 (Kubota et al. 2010, 2015b) and Core MD98-2195 (Ijiri et al. 2005) as well as residual $\delta^{18}O$ as a salinity proxy in Core KY07-04 PC01 (Kubota et al. 2010, 2015a, b). SST and residual $\delta^{18}O$ at Core KY07-04 PC01 and the errors ($\pm 1\sigma$) were derived by Paleo-Seawater Uncertainty Solver (PSU Solver) (Thirumalai et al. 2016) with the methodology of Kubota et al. (2019). Downcore profiles of relative abundances (%) of warm diatom indicators and *Thalassionema* variety index in Core KY07-04 PC01 were also shown. Gray hatches indicate MWP-A and YD periods. Horizontal broken lines denote pronounced decreases in warm diatom indicators during Holocene

Thalassionema frauenfeldii was relatively abundant in the western margin of the North Pacific (Tanimura et al. 2007). In this study, we counted *T. frauenfeldii* as separated the two morphological types *T. frauenfeldii* s.l. and *T. frauenfeldii* s.s. Simonsen (1974) described *Thalassiothrix frauenfeldii* (= *Thalassionema frauenfeldii* s.l.), *T. frauenfeldii* s.l. is reported from the open ocean of the western North Pacific (Hasle 2001; Tanimura et al. 2007). On the other hand, *Thalassionema frauenfeldii* s.s. is likely to be a coastal species because Hallegraeff (1986) and Sar et al. (2007) collected this from the Argentine and Korean coasts. In Core KY07-04 PC01, *T. frauenfeldii* s.l. gradually increased since the LGM, whereas *T. frauenfeldii* s.s. was relatively high abundances during the LGM to the deglacial period with a gentle peak centered at ~12 ka ago (Fig. 3). The overall trend suggests a transition from semi-closed to open ocean environments during the deglacial period.

Warm water taxa dwelling in the open ocean gradually increased since the LGM and reached ~30% at 8 ka ago (Fig. 3). Among them, *Nitzschia bicaipitata* is the major open-ocean species abundant in tropical to temperate oceans (Fryxell 2000), including in the western Pacific warm pool in the western equatorial Pacific with >28 °C sea-surface temperature (Kobayashi and Takahashi 2002) and Kuroshio region (Tanimura 1992). In Core KY07-04 PC01, relative abundances of *N. bicaipitata* were high between 12 and 5 ka ago, with a rapid increase near the core top (Fig. 3). Li et al. (2012, 2015) also reported a high percentage of *N. bicaipitata* for the last 400 ka in Core MD05-2908 from the southern Okinawa Trough off northeast of Taiwan. Because of the restricted *N. bicaipitata* distribution in the open ocean, abundant *N. bicaipitata* suggests strengthening Kuroshio inflow into the East China Sea. During the early to middle Holocene, Kuroshio intensified due to strengthening the Subtropical Gyre by precessional forcing (Isono et al. 2009; Yamamoto 2009).

4.2 Changes in surface water mass in the East China Sea since the LGM

Diatom assemblages dominated by *Paralia* spp. in Core KY07-04 PC01 indicate intensified Chinese coastal water whereas weak Kuroshio water in the northern East China Sea during the LGM. Planktic foraminiferal assemblage records also suggested enhanced coastal water during the LGM (Xu and Oda 1999; Ijiri et al. 2005). Reconstructed SSTs during the LGM were ranging from 19 to 22 °C in the northern East China Sea based on planktic foraminiferal Mg/Ca (Kubota et al. 2010; Ujiie et al. 2016), alkenone (Ijiri et al. 2005), and radiolarian transfer function (Matsuzaki et al. 2019) (Fig. 5). In the central and southern Okinawa Trough, reconstructed SSTs

during the LGM were between 21 and 24 °C (Sun et al. 2005; Chang et al. 2009a; Yu et al. 2009; Chen et al. 2010; Xu et al. 2013) (Fig. 5). These SSTs were 2–5 °C lower than the present ones but still within temperate to subtropical ranges, consistent with continuous occurrences of warm open-water diatom taxa in Core KY07-04 PC01 since the LGM. In addition, the regional high-resolution climate model study by (Vogt-Vincent and Mitarai 2020) supports scenario-based proxy records. Kuroshio kept flowing into the Okinawa Trough during the LGM but significantly weakened. However, Kuroshio's path and intensity during the LGM varied depending on the models. During the LGM, the Kuroshio path migrated to the south of the Ryukyu Islands suggested by a model (Kao et al. 2006). On the contrary, a simulation indicates stronger Kuroshio flowing into the Okinawa Trough (Lee et al. 2013).

Expansion of the nutrient-rich Chinese coastal water led to enhanced productivity in the glacial East China Sea (Ijiri et al. 2005; Chang et al. 2009a; Kubota et al. 2017; Matsuzaki et al. 2019). Dominant *Paralia* spp. in Core KY07-04 PC01 as an indicator of nutrient-rich coastal water (McQuoid and Nordberg 2003; Di et al. 2013; Liu et al. 2013) demonstrated high productivity in the glacial northern East China Sea. The Chinese coastal water prevailing in the northern East China Sea was an advancement of the river mouth of the Yellow River with sea-level drop during the LGM. Clay mineral compositions and Sr-Nd isotopes of the detrital matter revealed an ample detrital supply from the old Yellow River to the northern East China Sea during the LGM (Xu et al. 2014; Zhao et al. 2017, 2018; Beny et al. 2018). Tsushima Warm Current (TSWC) gradually intensified since 16 ka ago, elevated at 11 ka, and fully evolved at ~7 ka after the K-Ah eruption in the northern Okinawa Trough (Xu et al. 2014; Zhao et al. 2017). These timings were consistent with the increasing patterns of %warm diatoms and T-ratio (Fig. 5). In the central Okinawa Trough, the Yangtze River played a critical role in detrital supply (Diekmann et al. 2008; Dou et al. 2010a, b, 2012).

Relative abundances of *Paralia* spp., periphytic diatom taxa, in Core KY07-04 PC01 gradually decreased since the LGM, subsequently rapidly decreased from 15 to 14 ka ago (Fig. 3). One of the most pronounced deglacial events is meltwater pulse 1A (MWP-1A) between 14.6 and 14.3 ka ago when relative sea-level rose at Tahiti, Barbados, and Sunda Shelf about 10–20 m from –110 to –90 m (Deschamps et al. 2012). Due to the East China Sea location as categorized as a far-field (i.e., sites far away from past and present ice-covered regions (Yokoyama and Purcell 2021), a similar magnitude of relative sea-level rise is expected. With the rapid sea-level rise during MWP-1A, river mouths of the Yellow River and the Yangtze River must have retreated.

The supporting evidence is by records of clay mineral compositions and Sr-Nd isotopes of detrital matter, suggesting switch of the source region from the river to the continental shelves (Dou et al. 2010a, b, 2012; Xu et al. 2014; Zhao et al. 2017; Hu et al. 2020). Gradual increases in warm diatoms, T-ratio, and Mg/Ca SST in Core KY07-04 PC01 indicate a gradual intensification of Kuroshio during the deglacial period. During the Younger Dryas between 12.9 and 11.6 ka ago (Cheng et al. 2020), warm diatoms kept increasing, whereas Mg/Ca SST was relatively low (Fig. 5).

In the northern Okinawa Trough, Kuroshio intensified between 12 and 5 ka ago, reaching its maximum at ~8 ka ago based on diatom taxa living in warm, open water (Fig. 5). Multi-proxy records also indicate the intensified Kuroshio during late deglacial to middle Holocene, i.e., SST rise (Ijiri et al. 2005; Kubota et al. 2010, 2015b; Ruan et al. 2015; Zhao et al. 2015), deepening of the thermocline (Li et al. 2020), planktic foraminiferal assemblage (Xu and Oda 1999; Ijiri et al. 2005), floral changes of calcareous nannoplankton assemblage (Su and Wei 2005), sortable silt (Diekmann et al. 2008), terrigenous input from Taiwan (Dou et al. 2010a, b, 2012, 2016; Xu et al. 2014, 2019; Zheng et al. 2016; Zhao et al. 2017; Hu et al. 2020), organic carbon and reactive phosphorus (Shao et al. 2016; Li et al. 2018), mercury concentration (Lim et al. 2017), and redox sensitive metals (Zou et al. 2020). Warm diatoms showed several rapid decreases based on the direct comparison between diatom assemblage and Mg/Ca SST in Core KY07-04 PC01. Some of these events accompany Mg/Ca SST drops during the Holocene (Fig. 5). An event at 7 ka ago was the most prominent. Subsequently, Kuroshio intensity might have weakened during the late Holocene due to its southward migration by precessional forcing controlling the strength of the North Pacific subtropical gyre (Isono et al. 2009; Yamamoto 2009). However, a sudden increase in *N. bicapitata*, representative diatom species dwelling in the open ocean with high SST, was observed near the core top of KY07-04 PC01 (Fig. 3). High-resolution diatom assemblage record during the late Holocene in the southern Okinawa Trough showed high abundances of *N. bicapitata* for the last ~400 yrs (Li et al. 2015, 2012). Such high abundances of *N. bicapitata* over the Okinawa Trough is consistent with the finding of intensification of Kuroshio during the latest Holocene (Zhang et al. 2019), implying persistent poleward heat transport regardless of the weakening of the Atlantic Meridional Overturning Circulation (Summerhayes and Zalasiewicz 2018). Alternatively, the high *N. bicapitata* abundances might be related to the response to the global warming (Chen et al. 2019a) and southward course shift of the Yellow River discharged into the Yellow Sea between 1546 and 1855 A.D. (Saito and Yang 1995).

5 Conclusions

We conducted microscopic observations for diatom assemblages since the LGM in Core KY07-04 PC01 from the northern Okinawa Trough, East China Sea. The produced diatom assemblage data are the first centennial-scale resolution since the LGM in the East China Sea with SEM and LM photographs of the representative taxa. Most of the diatoms found in Core KY07-04 PC01 were marine taxa throughout the core, with a few freshwater/brackish water taxa. There was a substantial turnover of major diatom groups from periphytic to planktonic taxa during deglaciation between 17 and 14 ka ago. During the LGM and early deglaciation, the representative periphytic taxa were *Paralia* spp., abundant in the modern continental shelf region of the East China Sea covered by the Chinese coastal water. The advancement of the Yellow River mouth with a sea-level drop during the LGM was the plausible reason for the prevailing Chinese coastal water in the northern East China Sea. Rapid decrease in the relative abundances of *Paralia* spp. during 15–14 ka ago corresponded to MWP-1A, a major deglacial event with the rapid sea-level rise during 14.6–14.3 ka ago. Planktonic cold diatom taxa were less than 10% throughout the core, suggesting the oceanic environment in the northern Okinawa Trough has been temperate to subtropical even during the LGM. Planktonic diatom *Thalassionema* was the dominant diatom genus since 14 ka ago. A ratio of three *T. nitzschioides* varieties (var. *incurvatum*, var. *inflatum*, and var. *parvum*) in *Thalassionema nitzschioides* complex (T-ratio) increased since 12 ka ago and has reached its present level since 8 ka ago, responding to strengthening and northward migration of Kuroshio during early to middle Holocene by precessional forcing. Warm planktonic diatom taxa also showed a gradual increase from 12 to 8 ka ago. A sudden increase in *N. bicapitata*, warm open ocean species, was found near the core top, which might be related to the intensifying Kuroshio during the latest Holocene.

Abbreviations

CRDW: Changjiang River Diluted Water; LGM: Last Glacial Maximum; LM: Light microscope; MWP: Meltwater pulse; SEM: Scanning electron microscope; SSS: Sea-surface salinity; SST: Sea-surface temperature; TSWC: Tsushima Warm Current; YD: Younger Dryas.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40645-021-00456-1>.

Additional file 1: Tables S1 and S2. Counts of diatom valves and relative abundance (%) of diatom taxa in Core KY07-04 PC01.

Additional file 2: Plates 1-6. LM and SEM images of major diatom taxa in Core KY07-04 PC01.

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Authors' contributions

YO designed the study, analyzed the data, and wrote the manuscript. KS carried out microscopic observation and analyzed the data with technical support from SK. YM and YY conducted radiocarbon measurements. YK collected sediment core sample and analyzed Mg/Ca of foraminifera. All authors read and approved the final manuscript.

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Availability of data and material

The datasets supporting the conclusions of this article are included within the article and its additional files.

Declarations

Competing interests

The authors declare that they have no competing interest.

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