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Signatures of the late Holocene Neoglacial cold event and their marine–terrestrial linkage in the northwestern Pacific margin

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ABSTRACT

Marine microfossil assemblages in core sediments from the northern East China Sea (ECS) were investigated to understand late Holocene paleoclimatic changes in the northwestern Pacific margin. We find a pronounced alternation of ocean condition during the late Holocene characterized by an abrupt decrease in dinoflagellate cysts and Kuroshio water species of planktonic foraminifera centered at ca. 4000–2500 ¹⁴C yr BP. Compilation and merger of new and previously published data show that this oceanic event corresponds with terrestrial cooling and dry episodes in the northern China. The synchronicity between marine and terrestrial records is considered to be linked to a weakened Kuroshio influence that is in coupled with intensified winter monsoon, highlighting a significance of oceanic–atmospheric dynamics in determining moisture and heat distribution over both oceanic and terrestrial domains. Superimposed on the late Holocene, the synchronicity between this particular climatic shift in the northwestern Pacific and the Neoglacial cold events in the northern high-latitude regions is tentatively indicative of a global climate signal, possibly associated with dynamics of the North Pacific gyre system and the high latitude North Atlantic thermohaline circulation, and therefore positions of the mean latitude of the Kuroshio extension.

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Introduction

The marginal seas of the northwestern Pacific (e.g., Yellow Sea and East China Sea) are an important paleoclimate archive recording a wide variety of geologic and climatic processes in this area. As a transition between the world's largest continent and its ocean, these marginal seas contain sedimentary sequences that often provide detailed information regarding the evolution of continent–ocean–climate interactions through time (e.g., Ijiri et al., 2005; Li et al., 2007). Furthermore, understanding the climate systems of this region is particularly important, because it has strong societal relevance to the surrounded countries and worldwide. The East China Sea (ECS) is an open marginal sea in the northwestern Pacific and is considered to be a large source and reservoir of energy and materials originating from both land and ocean. The Kuroshio Current (KC), which covers the ECS shelf, is the main western boundary current of the northwestern Pacific. It is known to be a key component of the Asian climate system through the meridional transport of water mass, heat and freshwater, strongly affecting the climatic evolution of the adjacent continent, as well as ocean systems in the ECS shelf (e.g., An et al., 2000; Liu et al., 2007; Xiang

et al., 2007). Several lines of evidence suggest that paleoceanographic records from the ECS region can provide insight into the evolution of regional climate and hydrographic conditions in the western Pacific near East Asia (e.g., Lin et al., 1996; Li et al., 2007; Chang et al., 2008).

Research has revealed that much of the Holocene period can be characterized by abrupt, small-magnitude climatic fluctuations (e.g., Bond et al., 1997; Xiang et al., 2007; Yoo et al., 2009). Millennial-scale climate oscillations during the Holocene are well recorded in proxy records such as ice-rafted debris events in the subpolar North Atlantic (Bond et al., 1997, 2001), cooling events in the subtropical North Atlantic off West Africa (deMenocal et al., 2000; Marret et al., 2006) and Arabian Sea (Sirocko et al., 1996), and reduced rainfall episodes in Oman (Neff et al., 2001) and Dongge Cave in China (Dykoski et al., 2005; Wang et al., 2005). Of particular interest is a discernible climatic signature of the late Holocene recorded in northern China and the East and South China seas, being generally characterized by cooler and drier climatic conditions (Jin et al., 2004; Xiang et al., 2007). However, an integrated perspective for marine and terrestrial sequences in this region has been lacking, although it is of primary importance to understand mechanisms transferring such climatic variability between both domains.

Microfossil assemblages preserved in the sedimentary record have been widely applied in paleoceanographic and paleoclimatic

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studies. For example, the abundance and species composition of planktonic foraminifera in marine sediments are useful tools for reconstructing past surface-water hydrography (e.g., Gupta et al., 2006; Xiang et al., 2007), since the distributions of modern planktonic foraminifera are known to be controlled by water mass and circulation patterns as well as upwelling and biological productivity (Bé and Tolderlund, 1971; Hemleben et al., 1998). Additionally, major shifts in benthic foraminiferal communities have been used to identify changes in depositional environments (e.g., Lim et al., 2006; Kang et al., 2010) as well as bottom-water salinity (e.g., Kim and Kucera, 2000; Xiang et al., 2008). Over the last decade, the use of dinoflagellate cysts for reconstructing paleoceanographic and paleoenvironmental conditions has been increased in parallel with an improvements in our understanding of modern dinoflagellate cyst distributions in relation to environmental parameters (e.g., Marret and Zonneveld, 2003; Matthiessen et al., 2005; de Vernal and Marret, 2007; Kim et al., 2010).

In this study, microfossil assemblages in sediment cores from the northern ECS were investigated and compared with existing marine and terrestrial records in order to identify a mechanism transferring the late Holocene climate fluctuations between marine and terrestrial environments in the northwestern Pacific margin.

Environmental setting

The ECS is one of the marginal seas of the western Pacific Ocean, bounded on the east by Ryukyu Islands, on the south by the island of Taiwan, and on the west by mainland China and the Asian

continent (Fig. 1). It is connected to the South China Sea by the Taiwan Strait and with the East/Japan Sea by the Korea Strait, and it opens in the north to the Yellow Sea. The northwestern part of the ECS is characterized by a wide continental shelf with depths shallower than 200 m. The southeastern part of the ECS is occupied by the Okinawa Trough along the outer edge of the continental shelf that reaches up to ca. 2700 m in water depth (Zhang and Su, 2006).

The hydrography of the ECS is largely influenced by the KC, which originates from the North Pacific Equatorial Current. The KC enters the ECS along the east side of Taiwan and then flows into the Pacific through the south of Kyushu, Japan. A branch of the KC intrudes to the East Sea through the Korean/Tsushima Strait between Korea and Kyushu. Since the KC waters are warm (about 20 °C) and have relatively high salinities (about 34), it transports a large amount of heat and moisture from the tropics to the middle latitudes as it flows along the western edge of North Pacific (Hsueh, 2000; Ichikawa and Chaen, 2000). The northwestern part of the ECS is governed by coastal waters with lower temperatures and salinity under influences of two large rivers, the Yangtze River (Changjiang) and Yellow River (Huanghe). These rivers discharge a large amount of fresh water and terrestrial materials into the ECS, and their large nutrient input supports high primary production in the surface waters (Hama et al., 1997).

Sea surface temperature (SST) and salinity of the ECS are also regulated by the East Asian monsoons. The observed mean annual SST of the ECS is ~24.7 °C, with a seasonal range between ~28.6 °C (July) and ~21.8 °C (January). Mean annual sea surface salinity (SSS) is ~34.4, with a summer low of ~34.1 and a winter high of

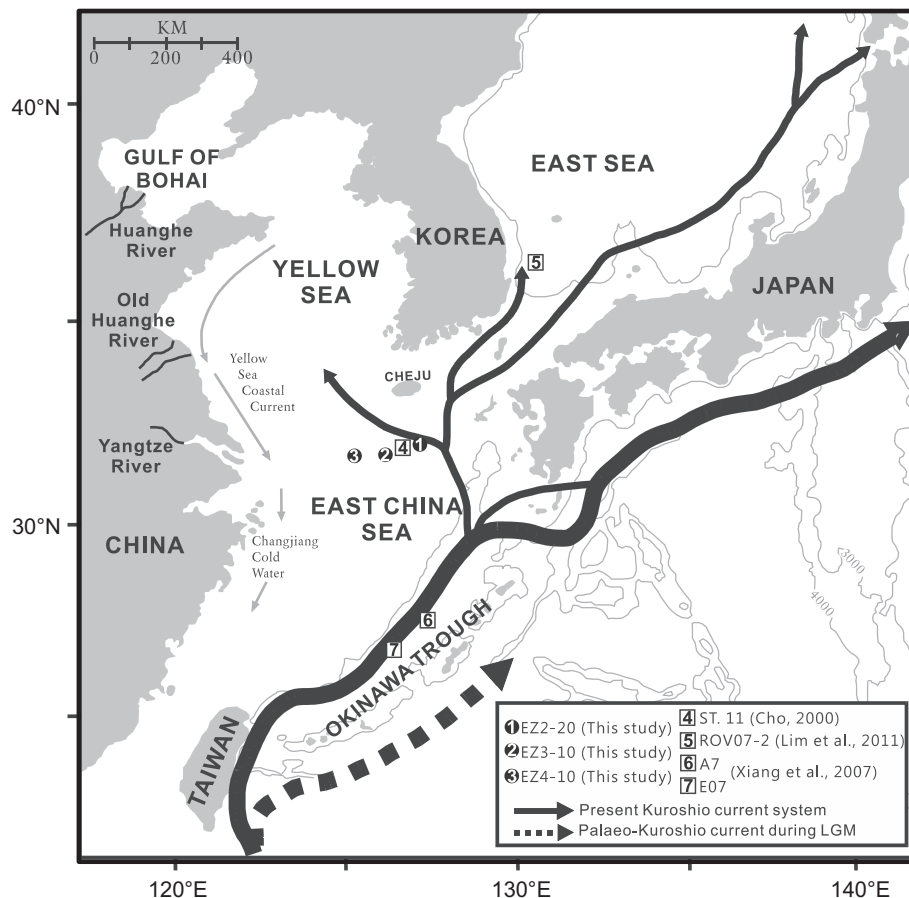


Fig. 1. The map showing the study area with the location of three piston cores collected for this study and previous reported cores, as well as the main path of the Kuroshio Current in the northwestern Pacific marginal seas. Black arrows indicate the Kuroshio Current and its branches (after Ujiie et al., 2003).

~34.7 (NOAA, 1994). During the summer, southerly winds bring warm, humid air and associated precipitation from low-latitude oceans to northeastern Asia and the adjacent seas, resulting in a large amount of freshwater discharge into the ECS. By contrast, during the winter monsoon, strong northerly winds bring cold, dry air from north-central Asia to the continent, reducing river discharge during these months (Chang et al., 2008).

Material and methods

Three sediment cores (EZ2-20, EZ3-10, and EZ4-10) were collected from the ECS continental shelf, located under the path of the KC, at water depths of 110, 65, and 50 m, respectively (Fig. 1). The cores were split lengthways, photographed, and logged. Details of sedimentary structures from some representative core sections were collected using X-ray radiographic photography. Grain-size analysis was conducted using a standard dry-sieving technique for the sand fraction ($>4\phi$) and by a pipette method for the mud fraction ($<4\phi$).

For dinoflagellate cyst analysis, cores EZ3-10 and EZ4-10 were subsampled at approximately 10-cm intervals. Approximately 5 g of subsamples were taken and treated following the method described by Cho and Matsuoka (1999). To prevent dinoflagellate cysts from being damaged by the oven-drying process, the original sample was divided into two parts: one was used to measure water content and the other was used for microscope analysis. To measure water content, the first half-sample was weighed wet and then oven dried at 70 °C for a day and reweighed; the weight difference was equivalent to the volume of lost water. The second half-sample was also weighed wet and then treated with ca. 50 ml of 10% hydrochloric acid (HCl) to remove calcium carbonate. Silicate materials were removed by applying ca. 50 ml of 47% hydrofluoric acid (HF) for about 24 h. After decanting and neutralizing with distilled water, the chemically treated samples were sonicated for 30 s and passed through 125 and 20 μm pore sized mesh sieves. Where possible, 300 dinoflagellate cysts were counted and identified from each sample with an inverted microscope (Nikon- Eclipse 55i) at 400 and 600 times magnification. Dinoflagellate cyst concentration in each sample was calculated as cysts/g dry weight of sediment: $N/W \times (1 - R)$, where N is a counted cyst number, W is a weight of an observed sediment, and R is a rate of water content of the sediment.

Analysis of planktonic foraminiferal assemblages was carried out on a total of 34 subsamples of EZ02-20 core sediment at approximately 10-cm intervals. The samples were oven-dried at 50 °C, weighed, and then washed through a 63- μm Tyler screen to separate the mud and sand fractions. After further drying, the

material was reweighed and the $>63 \mu\text{m}$ fraction was dry-sieved through a 150- μm screen. The resultant residue was divided into workable aliquot parts using a microsampler to ensure consistency in the splitting the samples. At least 200 planktonic foraminifera per sample were counted per sample and identified using a light microscope. For age dating and calculation of the relative ratio (%) between planktonic and total foraminifera abundance (P/T ratio), the benthic foraminifera in samples were counted and picked, but not identified.

Accelerator mass spectrometry (AMS) ^{14}C dating was performed on benthic foraminiferal tests (mixed species) and organic particles selected from a total of 16 horizons in cores EZ2-20, EZ3-10, and EZ4-10. AMS ^{14}C measurements were conducted at Beta Analytic, Inc. (Miami, FL, USA) and a 129-year reservoir age correction was applied (Kong and Lee, 2005). AMS ^{14}C ages of core samples are listed with the locations of cores in Table 1.

Results

Sediment characteristics and radiocarbon ages

The sediments of core EZ2-20 were mostly composed of greenish gray (5GY 2/1), homogeneous mud or muddy sand facies that displayed some bioturbation, as well as laminated sand/mud facies. The latter facies was particularly evident in the lower part of the core where the sediment showed a broad range of grain sizes of 2 to 8 ϕ because of the well-developed sand and mud laminations (Fig. 2). The radiocarbon ages of core EZ2-20 measured at depths of 30, 100, 200, 350, and 450 cm were 2860 ± 40 , 7090 ± 40 , 7140 ± 40 , $12,560 \pm 40$, and $16,120 \pm 140$ ^{14}C yr BP, respectively (Table 1). The sedimentary analysis and the radiocarbon dates of the core suggest that the core yields a complete depositional sequence since the LGM (Last Glacial Maximum). Sediments of core EZ3-10 are an olive grayish (5Y 4/2) and homogeneous mud facies with a mean grain size ranging from 8 to 9 ϕ (Fig. 2). Silt and clay contents ranged from 29–42% and 52–70%, respectively, with minor amounts of sand ($<10\%$). The radiocarbon ages at core depths of 20, 80, 200, 250, and 298 cm were 890 ± 40 , 1630 ± 40 , 1860 ± 40 , 2160 ± 40 , and 2470 ± 50 ^{14}C yr BP, respectively. These ages show that the sediments were continuously deposited since the late Holocene. Core EZ4-10 sediments, which were similar to those of EZ02-20 in sediment texture and sedimentary structure, were mainly dark olive gray (5Y 3/2), bioturbated and homogeneous sandy mud facies. Mean grain size varied between 5 and 8 ϕ with sand contents varying between 10% and 40%, except for the lowermost section (below a core depth of 400 cm) with well-developed rhythmic sand/mud laminations.

Table 1
AMS ^{14}C age data for cores EZ2-20, EZ3-10 and EZ4-10 from the study area.

Core No.	Core depth (cm)	Measured ^{14}C age (yr BP)	Error (\pm year)	Conventional ^{14}C age (yr BP)	Error (\pm year)	Materials	Laboratory Ref. No.
EZ2-20	30	2406	40	2860	40	benthic foraminifera	Beta198576
	100	6700	40	7090	40	benthic foraminifera	Beta198578
	200	6740	40	7140	40	benthic foraminifera	Beta198579
	350	12,650	40	12,560	40	peat	Beta203467
	450	16,080	140	16,120	140	organic sediment	Beta203468
EZ3-10	20	500	40	890	40	benthic foraminifera	Beta204935
	80	1240	40	1630	40	benthic foraminifera	Beta204936
	200	1470	40	1860	40	benthic foraminifera	Beta204937
	250	1780	40	2160	40	benthic foraminifera	Beta-221825
	298	2070	40	2470	40	benthic foraminifera	Beta204938
EZ4-10	90	1460	40	1840	40	benthic foraminifera	Beta221827
	210	2180	40	2570	40	benthic foraminifera	Beta204941
	365	3960	40	4350	40	benthic foraminifera	Beta204942
	480	22,410	130	22,450	130	organic sediment	Beta207360
	510	25,000	190	25,020	190	organic sediment	Beta207361

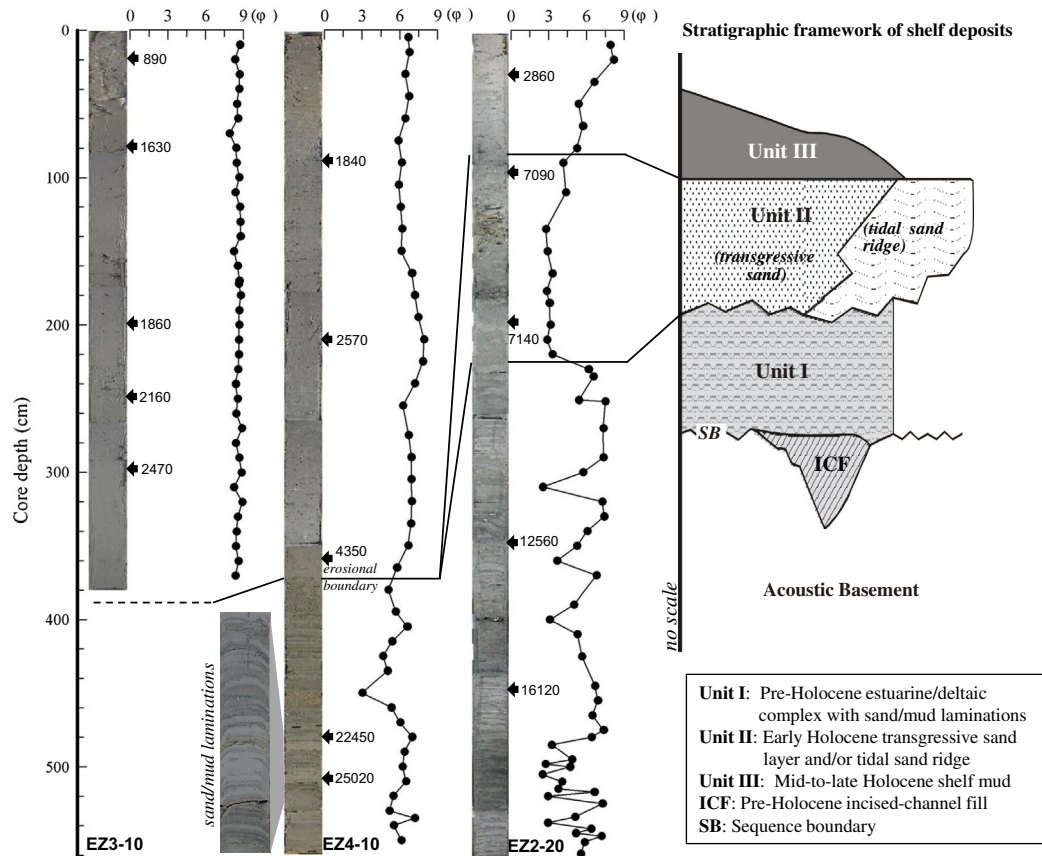


Fig. 2. Stratigraphic correlation of three cores from the study area and late Pleistocene stratigraphic framework of northern East China Sea shelf deposits (after Yoo et al., 2002). Numbers with arrows are radiocarbon ages (^{14}C yr BP).

The radiocarbon ages at core depths of 90, 210, 365, 480, and 510 cm were 1840 ± 40 , 2570 ± 40 , 4350 ± 40 , $22,450 \pm 50$, and $25,020 \pm 50$ ^{14}C yr BP, respectively. Of particular note is the considerable age gap at ca. 380 cm depth of the core (Fig. 2). This suggests that a strong erosional process affected the study site during the post-glacial transgression period, followed by resedimentation at 6000–5000 ^{14}C yr BP when the sea level neared its present level (e.g., Kong et al., 2006).

Considering the ^{14}C age dating and lithologic characters of the cores, together with geochemical, micropaleontological, and seismic stratigraphic data of several previous studies (Lim et al., 2000; Yoo et al., 2002; Hyun et al., 2006; Rho, 2009; Kang et al., 2010), the integrated evolution history of core sediments from the northern shelf of ECS can be divided into three stages, separated by sharp lithologic changes bounded by erosional surfaces: (1) a mid-to-late Holocene shelf mud facies (present to ca. 7000 ^{14}C yr BP); (2) an early Holocene sand facies formed during transgression of sea level (ca. 10000 to 7000 ^{14}C yr BP); and (3) late Pleistocene coastal sand/mud deposits (ca. 25,000 to 11,000 ^{14}C yr BP) (Fig. 2). In particular, the lower sections of cores EZ2-20 and EZ4-10 containing well-developed sand and mud laminations are interpreted as deposits of a tide-influenced subtidal deltaic/estuarine environment during the sea-level lowstand when the paleo-shoreline was located 120 m below present-day sea-level (Saito et al., 1998; Kang et al., 2010).

Vertical variations of microfossil assemblages

We examined planktonic foraminiferal assemblages of core EZ02-20 sediments, spanning the ca. 20,000 ^{14}C yr BP. The foraminiferas were not identified in the lower sediment sections

(<220 cm) because of its low occurrence (Table 2). In the samples, a total of 37 species were identified, all of which are commonly found in the modern northwestern Pacific Ocean and the ECS. The most abundant species with maximum percentages greater than 10% in at least one sample included *Globigerina bulloides*, *Globigerinita glutinata*, *Globigerinoides ruber*, *Neogloboquadrina dutertrei*, and *Pulleniatina obliquiloculata*. These five species account for more than 65% of the total planktonic foraminiferal assemblage in all subsamples of the core. *Globigerina falconensis*, *Globigerinoides sacculifer*, *Neogloboquadrina incompta*, and *Turborotalia crassaformis* also frequently occurred at maximum levels of less than 5%. The most common planktonic foraminifera in the upper section of the core (0–220 cm), which represents the mid-to-late Holocene deposits, was *G. bulloides* at 17.4–37% and showed an increased abundance until 90 cm, after which it exhibited gradual decline (Fig. 3b). *G. ruber*, *N. dutertrei*, and *P. obliquiloculata* vary in ranges of 8.2–22.4%, 9.7–20.4%, and 4.3–16.2%, respectively. The abundance, assemblage, and P/T ratio changed markedly at core depths of 220 cm, corresponding to ca. 7000 ^{14}C yr BP (Fig. 3a). The planktonic foraminifera in the sediments of lower section below 220 cm is low (<50 number g^{-1}) in occurrence, but it largely increases up to ca. 7500 number g^{-1} in the upper section. The P/T ratio gradually increased from an average of 19% below 220 cm to 42% above 200 cm. These results show an apparent paleoenvironmental change in the northern ECS shelf associated with a global sea level change during the late Pleistocene, involving a termination of the coastal water stage over the shelf at approximately 7000 ^{14}C yr BP when the warm KC began to flow into the ECS. The intrusion of warm Kuroshio waters at 8000–7000 ^{14}C yr BP is also recorded in several cores taken from marginal seas of the northwestern Pacific (Liu et al., 1992; Sawada and Handa, 1998; Kawahata et al., 2003; Kong et al., 2006).

Table 2
Species composition and relative percentage (%) of planktonic foraminifera in the core EZ02-20 from the northern East China Sea.

Species/depth (cm)	0	10	15	20	25	30	35	40	45	50	60	70	80	90	100	120	140	200	220	360	380	400	420	440	480	
<i>Beella digitata</i>														0.5				0.5								
<i>Globogerina angustum-bilicata</i>			1.3				0.7	0.4		0.4	0.4		0.4		0.5				2.2		5.0	7.1		12.5		
<i>Globigerina bulloides</i>	30.0	30.7	28.3	21.6	37.2	29.1	31.8	27.7	36.3	21.5	23.8	21.9	25.6	34.5	35.5	25.7	25.4	20.9	17.4	100.0	15.0	28.6	15.4	25.0		
<i>Globigerina calida</i>					0.9	0.5			0.9	0.4	0.4		0.4				0.8									
<i>Globigerina falconensis</i>	4.2	4.7	3.0	2.6	3.7	3.6	5.2	3.5	3.8	3.6	4.3	3.3	2.9	1.8	4.1	3.7	4.7	1.5	2.2							
<i>Globigerina foliata</i>																0.5	2.1	1.0	4.3							
<i>Globigerina quinqueloba</i>	0.7	2.3	1.3		0.6	1.5	1.0	2.2	0.4	1.1	0.7	1.0		0.9	0.9	0.5	1.3	0.5			25.0	7.1				
<i>Globigerina rubescens</i>	0.7	0.9	2.1	1.9		1.0	1.0	3.0	0.9	2.2	2.1	0.5	0.8	1.4	1.4	0.9	2.5	2.0			5.0					
<i>Globigerinella aequilateralis</i>	2.1	0.5	0.4	3.9	0.9	1.0	1.4	1.7		1.5	0.4	1.4	1.2	0.9		1.8	0.4	1.0	2.2							
<i>Globigerinita glutinata</i>	8.1	5.1	8.0	4.2	7.0	10.7	7.3	9.1	9.8	8.4	6.4	7.1	7.4	7.7	14.5	9.2	8.5	8.7	15.2		5.0	14.3	7.7	25.0		
<i>Globigerinita parkerae</i>															0.5											
<i>Globigerinita uvula</i>			0.4							0.4			0.8				0.4									
<i>Globigerinoides conglobatus</i>	0.7	0.0		3.2	0.9	1.0	0.3		0.9	1.1	1.1	1.0	1.2	0.9	0.5	0.9	0.8	3.1	4.3							
<i>Globigerinoides immaturus</i>		1.4						0.9			0.4		0.4		0.5	1.8	3.0	2.0	2.2							
<i>Globigerinoides quadrilobatus</i>	2.8	2.8	0.4	2.9	0.3	1.0	1.0	1.3	1.7	1.8	1.8	3.3	2.1	1.8	0.9		0.4	1.0								
<i>Globigerinoides ruber</i>	17.0	14.9	22.4	18.4	17.4	18.9	15.2	13.0	15.0	17.5	19.5	16.2	13.2	10.5	8.2	18.3	13.1	12.8	10.9		15.0	7.1	15.4	25.0		
<i>Globigerinoides pyramidalis</i>	0.4																0.4									
<i>Globigerinoides sacculifer</i>	1.8	1.4	3.0	4.2	2.1	3.6	2.8	2.2	3.4	2.2	1.8			2.7	0.9	1.4		0.5	2.2							
<i>Globigerinoides tenellus</i>			0.4				0.7			0.4		1.4		0.9		0.5	0.8	1.0					7.7			
<i>Globigerinoides</i>	0.4																									
<i>Globorotalia menardii</i>		0.5	0.4	1.0		0.5	1.0	0.4	0.9	0.7	0.4					0.9										
<i>Globorotalia obesa</i>		0.9	0.4			1.0	0.3	0.4		0.4	0.4	0.5		0.5												
<i>Globorotalia truncatulinoides</i>		0.5																								
<i>Globorotalia unguolata</i>	0.4					0.5	0.3	0.4		0.7	1.4	0.5	1.7		0.5	0.5		1.5			5.0	7.1				
<i>Globorotalia</i>												0.5														
<i>Globorotaloides hexagona</i>																		0.5								
<i>Hastigerina pelagica</i>		0.5														0.9										
<i>Neogloboquadrina dutertrei</i>	12.7	12.6	9.7	16.1	10.1	13.3	9.7	13.4	11.1	20.4	18.4	15.7	16.5	15.9	15.5	11.5	14.0	16.8	17.4		15.0	28.6	23.1			
<i>Neogloboquadrina incompta</i>	1.8	6.0	5.1	1.3	6.4	4.1	3.5	3.9	6.0	4.4	2.8	5.7	4.5	4.5	6.4	6.0	6.4	4.6	4.3		10.0		15.4			
<i>Neogloboquadrina pachyderma (s)</i>			1.3		0.3		3.1																			
<i>Neogloboquadrina pachyderma (d)</i>	2.8	0.5	0.8		1.8	0.5	1.0	0.9	2.6	2.5	1.1	1.9	2.5	3.2	1.4	0.9	1.7	2.0	2.2					12.5		
<i>Orbulina universa</i>	0.4		0.4	0.6	0.3			0.9	0.4			0.5	0.8		0.5											
<i>Pulleniatina obliquiloculata</i>	10.6	12.1	9.7	13.5	8.5	7.1	9.3	8.7	4.3	6.9	9.9	16.2	16.1	10.9	7.3	9.6	5.1	8.2	13.0				7.7		100.0	
<i>Pulleniatina sp. A</i>											0.7					1.8	1.3	4.6								
<i>Turborotalia crassaformis</i>	2.5	1.9	1.3	4.5	1.5	1.0	2.4	6.1	1.7	1.5	1.8	1.4	1.2	0.5	0.5	0.9	1.3									
<i>Turborotalia inflata</i>							0.3			0.7							0.4	1.5					7.7			
<i>Turborotalita humilis</i>							0.3																			
Miscellaneous (fragmented specimens)																1.8	5.1	3.6								
Total number of planktonic forams	283	215	237	310	328	196	289	231	210	275	282	210	242	220	220	218	236	196	46	1	20	14	13	8	1	

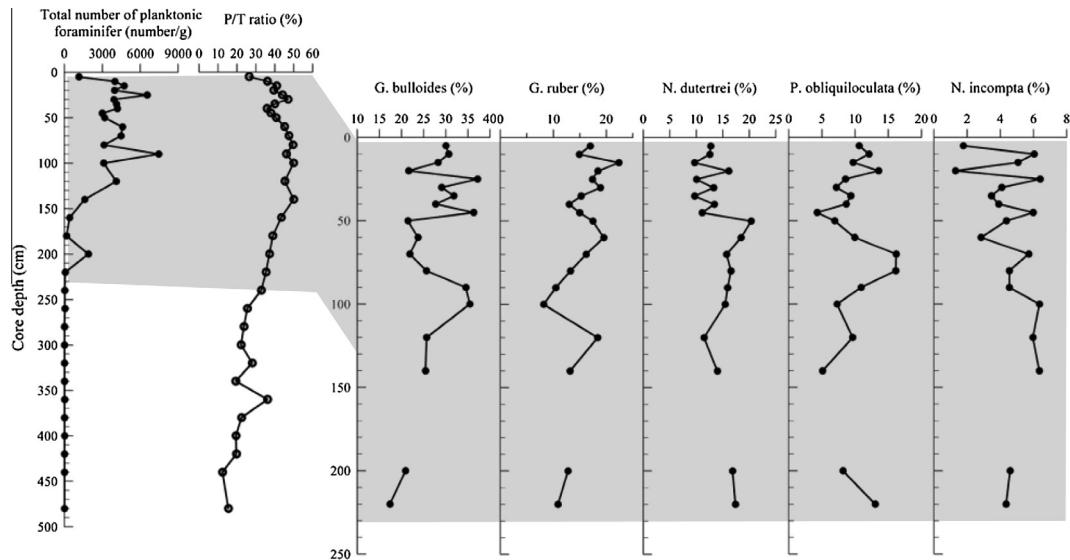


Fig. 3. Down-core variations in total number of planktonic foraminifer, relative abundance of some major species and P/T ratio in core EZ2-20.

In total, 14 genera and 24 dinoflagellate cyst taxa were identified from cores EZ3-10 and EZ4-10 (Table 3). Cyst concentrations ranged between 1000 and 6000 number g^{-1} , except for core depths below 400 cm (<200 cysts g^{-1}). In core EZ2-20, the dominant species were *Spiniferites bulloideus* (23–64%), *Spiniferites* spp. (12–47%), *Operculodinium centrocarpum* (0–10%), *Spiniferites delicatus* (0–10%), *Nematosphaeropsis labyrinthus* (0–26%), and *Tuberculodinium vancampoae* (0–10%) (Fig. 4). Similarly, in core EZ4-10 the dominant species included *Spiniferites bulloideus* (0–67%), *Spiniferites* spp. (0–40%), *Brigantedinium* spp. (0–50%), *Spiniferites mirabilis* (0–14%), *Operculodinium centrocarpum* (0–25%), and *Spiniferites delicatus* (0–12%) (Fig. 4). In core EZ4-10, dinoflagellate cysts were rarely observed or absent in the late Pleistocene deltaic/estuarine sediments. In contrast, dinoflagellate cyst concentrations showed an increase in the upper core sections, indicating a major transition from a deltaic/estuarine environment to a full-oceanic environment suitable for colonization by dinoflagellates. The dinoflagellate cyst assemblages of the Holocene deposits were characterized by a predominance of the gonyaulacoid group (e.g., genera *Spiniferites*, *N. labyrinthus*, *O. centrocarpum*, and *Lingulodinium machaerophorum*), which constituted ca. 83–99% and 79–94% of total cyst concentrations in cores EZ3-10 and EZ4-10, respectively (Fig. 5). Such notable increase in the gonyaulacoid species indicates increased nutrient loadings in the upper water column of the northern ECS since the onset of the early Holocene (Kim et al., 2012).

Discussion

Signatures of the late Holocene cold event in the ECS shelf

Sedimentological and micropaleontological records of the core sediments from the study area show that there was a major environmental change from a pre-Holocene deltaic/estuarine environment to a full-oceanic environment of the mid-to-late Holocene in the northern ECS shelf (Fig. 2). The evidence presented here suggests that the present-day oceanographic conditions were established over the shelf region at around 7000 ^{14}C yr BP. Coinciding with the flooding of the estuarine shelf, significantly improved marine productivity is indicated by a notable increase of planktonic foraminifera and dinoflagellate cysts in Holocene deposits (Figs. 3 and 5). Such improvement of marine productivity may be primarily caused by the post-glacial sea-level rise which resulted

in an expansion of marine habitats suitable for micro-organisms. Additionally, we suggest that the increase of the micro-organism community in the shelf water can be attributed, at least in part, to enhanced nutrient supply by palaeo-river discharge from the adjacent continent. The suggested postglacial nutrient enrichment corresponds in time with the Holocene climatic optimum that developed at 10,000–7500 ^{14}C yr BP and terminated at 5000–2000 ^{14}C yr BP (An et al., 2000; An et al., 2006). Considering that the Holocene climatic optimum is regarded as the time of maximum precipitation in central and eastern China (e.g., Bates and Jackson, 1987; Shi et al., 1993), increased moisture availability over the Chinese continent would have resulted in a massive river discharge and thus an increased nutrient supply to the northern ECS region. In the late Holocene, however, the postglacial marine productivity increase appears to be punctuated, notably at between 4000 and 2500 ^{14}C yr BP (Fig. 5). A recently published dinoflagellate cyst record from this area demonstrated that the lower concentration of dinoflagellate cysts during this period indicates a deterioration of nutrient availability (Kim et al., 2012). Similar trends can be observed in a previous dinoflagellate cyst investigation on the northern ECS shelf sediments (Cho, 2000), where an interval of low dinoflagellate cyst concentrations (core ST-11; location indicated in Fig. 1) points to the late Holocene period (Fig. 5). We, therefore, suggest that the late Holocene reduction in dinoflagellate cysts, coherently observed in the three core records, reflects a deterioration of nutrient availability in the northern ECS shelf environment.

Furthermore, the late Holocene deterioration of oceanic condition, in terms of sea-surface temperatures (SSTs), is clearly implicated in variations of the planktonic foraminiferal assemblage of core EZ2-20. On the basis of previous studies that analyzed relationships between occurrence of recent planktonic foraminifera assemblages and oceanographic conditions in the northwestern Pacific, the equatorial Pacific, and the ECS, planktonic foraminifera can be classified into four groups (Bé, 1977; Thompson, 1981; Wang et al., 1985; Li et al., 1997; Xu and Oda, 1999; Ujiie and Ujiie, 1999; Ujiie et al., 2003; Ijiri et al., 2005; Lim et al., 2006): tropical-subtropical assemblage (Group A), Kuroshio assemblage (Group B), cold assemblage (Group C), and coastal water assemblage with low salinity and/or low temperature (Group D) (Table 4). As shown in vertical profiles of planktonic foraminiferal assemblage in the core EZ2-20 (Fig. 6), a prominent decline in the tropical-subtropical

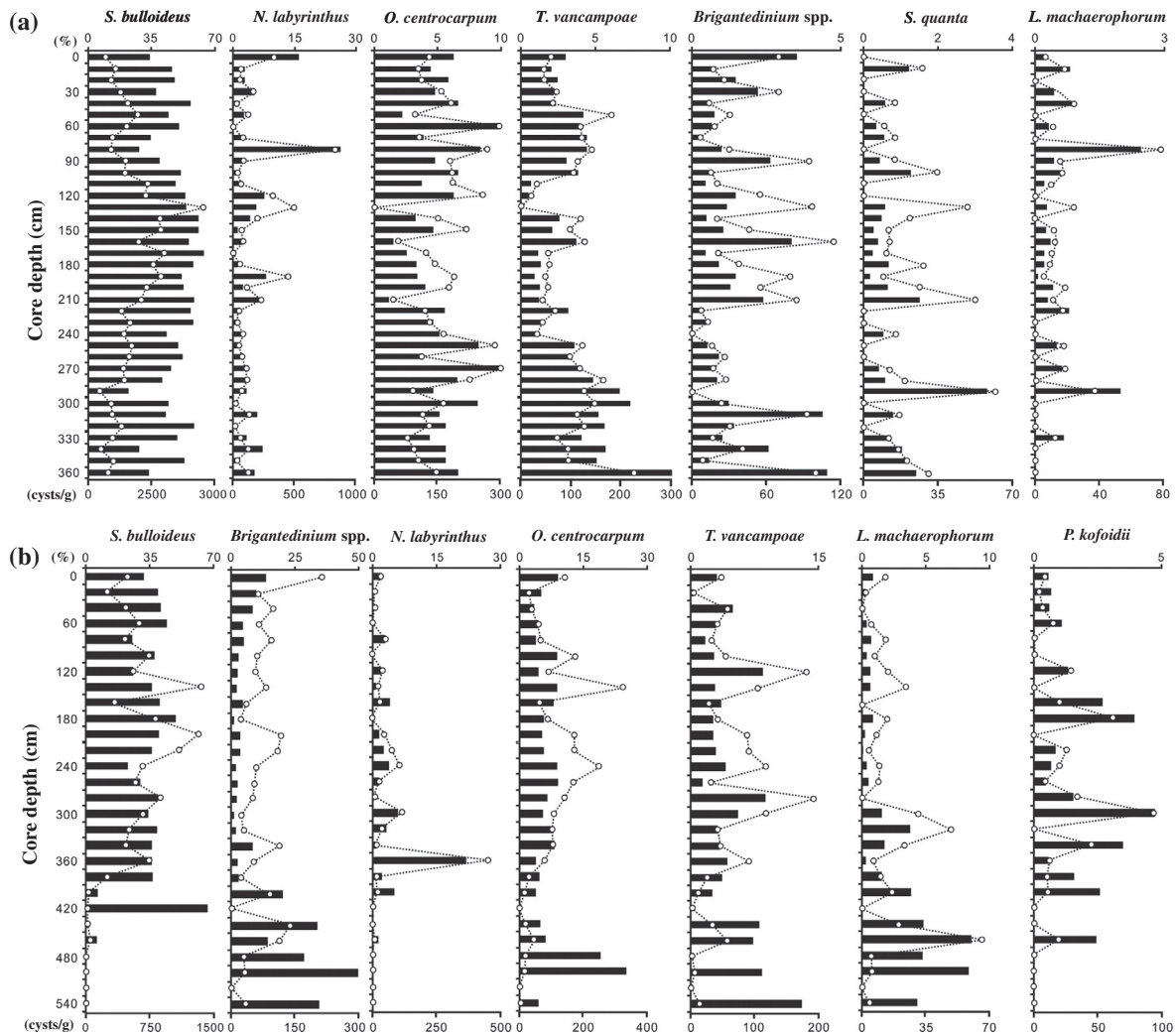


Fig. 4. Total numbers (black bar) and relative abundance (open circle) of major dinoflagellate cysts from cores EZ3-10 (a) and EZ4-10 (b).

species and the warm Kuroshio water species together with a marked increase in cold and coastal water species at 4500–2500 ^{14}C yr BP clearly point to reduced SSTs and sea-surface salinity (SSS) as a result of a weakened influence of the warm KC waters on the northern ECS. Taken together, the synchronous changes between dinoflagellate cyst and planktonic foraminiferal assemblages during the late Holocene point to a major environmental shift in nutrient availability as well as SSTs, linked to a weakened KC influence over the northern ECS shelf and the termination of the Holocene climatic optimum.

A global perspective on the late Holocene Neoglacial events

The late Holocene climatic events of the cores in this study show good correspondence with other marine records from the northwestern Pacific margin. The reduced nutrient availability and surface-water productivity during the late Holocene period have been reported from the Ulleung Basin of the East Sea, where the carbonate content of the sediments showed an abrupt decrease during the period 3600–2500 ^{14}C yr BP (Lim et al., 2011). In the middle Okinawa Trough in the South China Sea (SCS) (Xiang et al., 2007), the Holocene sediments are generally dominated by warm water species such as *G. ruber*, *G. sacculifer*, *G. glutinata*, and *P. obliquiloculata* (A7 and E017 cores; sampling sites are indicated in Fig. 1). However, for the period between 4600 and

2300 cal yr BP, a remarkable decrease in the Kuroshio water species *P. obliquiloculata* and an increase in the coastal water species *G. bulloides* were recorded (Fig. 7). Similar records of the so-called *Pulleniatina* minimum event have been found in previous studies (e.g., Ujiie and Ujiie, 1999; Ijiri et al., 2005; Jian et al., 2000). In Lee et al. (2010), summer and winter SSTs of core sediments from the southeastern part of the Ulleung Basin in the East Sea register a notably lower value at around 3000 cal yr BP. Such low SSTs in East Sea are also indicated by the decrease of *Fragilariopsis doliolus* and the diatom-estimated temperature (Koizumi et al., 2006). Consequently, these coherent late Holocene climatic events recorded in the northwestern Pacific marginal seas (i.e., East Sea, SCS, and ECS) suggest a cooling of surface waters in association with a sudden decrease in the warm Kuroshio water influence.

The Kuroshio water originates from subtropical and tropical regions with low nutrient contents near the surface (Chen, 1996). Therefore, the decreased marine primary productivity during this time period would not be directly affected by fluctuations of the Kuroshio water input itself. Several studies suggested that freshwater discharges from large rivers (e.g., Changjiang) in the adjacent continent are a main source of nutrient input to the ECS region (Beardsley et al., 1985; Chang et al., 2003). Therefore, we speculate that the deterioration of primary marine productivity superimposed on the SST cooling trend in the northern ECS shelf are attributable to an abrupt change in moisture contents over the adjacent

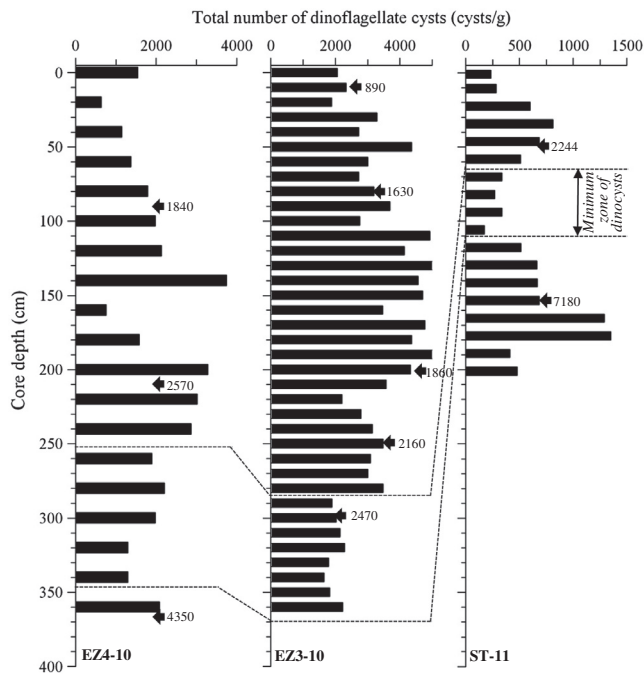


Fig. 5. Correlation in vertical variations of total dinoflagellate cyst concentrations in cores EZ3-10, EZ4-10 and ST-11. Numbers with arrows are radiocarbon ages (^{14}C yr BP).

Table 4

Four faunal groups of planktonic foraminifera based on modern planktonic assemblages of the Pacific marginal seas (after Lim et al. 2006).

Species	Water mass
Assemblage A	
<i>Globigerinoides ruder group</i> (<i>G. ruder</i> + <i>G. pyramidalis</i>)	Tropical-subtropical water
<i>Globigerinoides conglobatus</i>	
<i>Globigerinoides sacculifer</i>	
<i>Globigerinoides cf. sacculifer</i>	
<i>Globigerinoides tens</i>	
<i>Globigerinoides aequulateralis</i>	
Assemblage B	
<i>Globorotalia menardii</i>	Kuroshio water
<i>Neogloboquadrina dutertrei</i>	
<i>Pulleniatina obliquiloculata</i>	
Assemblage C	
<i>Globorotalia truncatulinoides</i>	Cold water
<i>Neogloboquadrina incompta</i>	
<i>Neogloboquadrina</i>	
<i>Pachyderma(s)</i>	
<i>Neogloboquadrina</i>	
<i>Pachyderma(d)</i>	
<i>Turborotalia inflata group</i> (<i>T. inflata</i> + <i>T. crassaformis</i>)	
Assemblage D	
<i>Globigerina bullioides</i>	Coastal water (low salinity and/or low temperature)
<i>Globigerina calida</i>	
<i>Globigerina quinqueloba</i>	

continent, which in turn controls nutrient supplies into the surface waters. This interpretation is supported by previous work on terrestrial records from northern China. According to Jin et al. (2004), climate proxy data from the Daihai Lake in northern China show that Holocene climate oscillations, including the Hypsithermal and the Neoglaciation, were punctuated by several decadal-to-millennial-scale changes from warm to cool and/or wetter to drier conditions (Fig. 7). Sediment records from the Daihai Lake

suggest that the warm and humid Hypsithermal period was resulted in a significant enhancement of terrestrial chemical weathering and a gradual increase in terrestrial plants. This suggestion is also supported by other high lake level records between ~9000 and 4000 years ago (Zhang, 1937; Wang and Li, 1990; Wang et al., 1990). After the end of the Hypsithermal warming interval (ca. ~3500 to 4000 years ago), the lake sediment records indicated limited terrestrial plant growth in semi-arid and semi-humid regions of northern China implying lowered temperatures and reduced weathering. A similar trend of terrestrial cooling linked to growing aridity have also been reported from other parts of the East Asian continent including Korean peninsula (e.g. Chung, 2011 and references therein). The climate transition from warmer/wetter to cooler/drier conditions in the northern Asia during the late Holocene coincides with Holocene fluctuations of mountain glaciers on the Tibetan Plateau. During the Early Holocene (10,000–7500 years ago), high lake levels and peat development in the Tibetan Plateau and surrounding areas indicate relatively wet and warm paleoclimatic conditions. These conditions were followed by the Holocene climatic optimum (7500–3000 years ago), which features warmer conditions than the present day (Gasse et al., 1991; Holland et al., 1991; Wang and Fan, 1987; Beug, 1987; Wang, 1987). Later, a negative trend occurred during the late Holocene. The cooling episode of the late Holocene is characterized by glacial advances over much of the Tibetan Plateau (Lehmkuhl, 1997; Fig. 7). In conclusion, the late Holocene terrestrial climatic transition in northern China appears to be synchronous with the oceanic environmental shift in the northern ECS shelf, reflected in our microfossil records. This finding suggests a close linkage between marine and terrestrial processes in past climatic changes in the northwestern Pacific margin. Given that SST variations in monsoonal regions have a crucial role in modulating land-sea heating and pressure gradients, and thus directly affecting the intensity of precipitation and runoff patterns over the adjacent continent (e.g., Schefuß et al., 2003; Weldeab et al., 2005), a possible explanation for the enhanced aridity over northern China during the late Holocene period involves SST cooling events associated with the weakened KC. In parallel, the shift in these late Holocene marine and terrestrial records of the northwestern Pacific margin is coeval with records of climatic variations observed in northern high latitude regions. The so-called Neoglaciation (or Neoglaciation) interval that began in the mid-Holocene and lasted more than 2000 years has been characterized by a marked sea-ice expansion over the East Greenland shelf (Jennings et al., 2002) and the western Arctic Ocean such as Chukchi Sea shelf (de Vernal et al., 2005) and the Canada Basin (Farmer et al., 2011), coastal glacier expansions over the Gulf of Alaska (Calkin et al., 2001), intensely erosive storms along the Chukchi Sea coast (Mason and Barber, 2003) and pronounced cooling events in the western Bering Sea (Razjigaeva et al., 2004). This trend supports the notion that climatic events of the northern Pacific Ocean are closely linked to the global climate system through hydrological dynamics in the Pacific sector of the Arctic Ocean (Woodgate et al., 2007, 2010; Hu et al., 2010, 2012).

In the northwest Pacific marginal seas, the weakened KC and reduced SSTs during the late Holocene have often been linked to an intensified winter monsoon and strengthened coastal currents (Li et al., 1997; Jian et al., 2000). However, it has recently become clear that the Holocene climatic fluctuations recorded in the ESC and SCS are closely linked to the path and strength of the KC in the East Asian marginal seas (Ijiri et al., 2005; Xiang et al., 2007; Chang et al., 2008). Therefore, we speculate that the suggested integration of both marine and terrestrial signals in the northwestern Pacific margin during the late Holocene could be related to global, not only regional climatic processes. In particular, the synchronicity of the late Holocene climatic events between the middle latitude northwestern Pacific margin and the northern high-latitude region

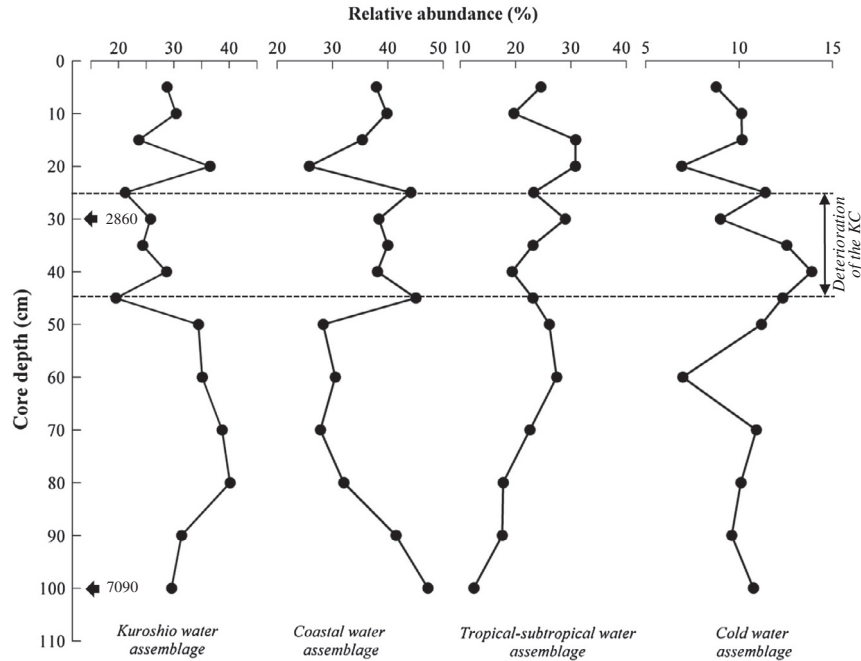


Fig. 6. Down-core variation in the relative abundances of four planktonic foraminifer assemblages during the mid-to-late Holocene periods. Note that the abrupt change in their assemblage between 25 and 45 cm, corresponding to approximately 3500–2800 years BP. Numbers indicate the radiocarbon ages (^{14}C yr BP).

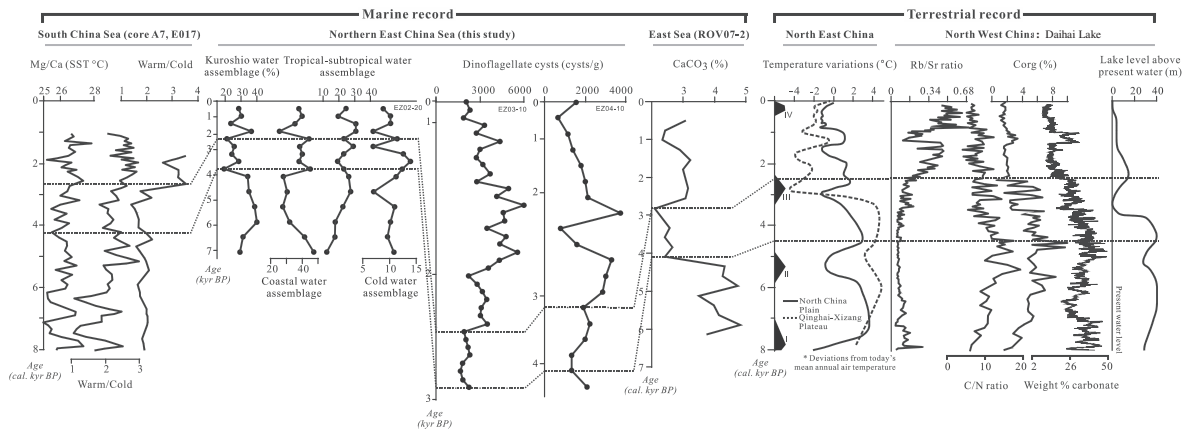


Fig. 7. Integrated marine-terrestrial proxy records in the northwestern Pacific margin for the late Holocene period. Terrestrial records from: temperature variations in the North East China (after Lehmkühl, 1997), Rb/Sr ratio, C/N ratio, C_{org} , weight percent carbonate and lake level in the North West China (after Jin et al., 2004). The interval of the late Holocene climatic event is indicated by dotted lines.

highlights a role of the global ocean circulation system, which regulates dynamics of the North Pacific gyre and the high-latitude North Atlantic thermohaline circulation, and therefore the mean latitude of the Kuroshio extension (Sawada and Handa, 1998; Isono et al., 2009). This notion is supported by recently published statistical analysis of a global set of Holocene time series from palaeoclimate archives (Wanner et al., 2011), in which the cooling event between 3300 and 2500 yr BP was hypothetically explained by fluctuations of the thermohaline circulation, as well as interconnected dynamics between the North Atlantic and Pacific regions.

Conclusions

Records of microfossil assemblages, including dinoflagellate cysts and planktonic foraminifers, in three piston cores from the northern shelf of the ECS indicate a marked change in paleo-depositional environments in the northern ECS since the LGM from a

deltaic/estuarine environment to a fully-oceanic environment. A rapid increase in dinoflagellate cysts and planktonic foraminifera during the early to mid-Holocene interval points to optimized climatic conditions in terms of SSTs and nutrient availability. In contrast to the warm and wet Holocene climatic optimum period, the late Holocene interval, particularly between 4000 and 2500 ^{14}C yr BP, registers a remarkable decrease in dinoflagellate cysts and a sudden increase in cold-water planktonic foraminiferal species, suggesting a weakened KC influence. The correlation between the deteriorated oceanic condition and terrestrial cooling and dry episodes in northern China highlights a significance of atmosphere-ocean dynamics regulating moisture and heat distribution over the northwestern Pacific margin. The late Holocene ocean-land climate fluctuations in the northwestern Pacific are synchronous to the Neoglacial events recorded in areas farther to the north. This might imply that the particular event, superimposed on the late Holocene, was not localized to the northwestern Pacific margin and represents a global climate signal in which mechanisms

transferring climatic variability between different latitudes and systems are embedded. Our study also emphasizes an important role of the global ocean circulation system in the climatic synchronicity between different latitudes and systems. Further studies are needed to correlate existing records of pure marine or terrestrial sequences for better understanding on the links between the ocean-land processes at different timescales covering a wide latitudinal transect including a number of atmospheric, terrestrial, and marine systems with different sensitivity to climatic changes.

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