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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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ABSTRACT

We generated a 42,000-year record of TEX_{86} (TEX^L_{86} and TEX^H_{86}) from core MD98-2195 to better understand changes in the hydrology of the East China Sea (ECS) in the last glacial period. The TEX_{86}-derived temperature showed an intense cooling in the last glacial period, whereas U^K_{37}-derived spring sea surface temperature (SST) and foraminiferal Mg/Ca-derived summer SST showed a much smaller-scale cooling. The difference between the TEX_{86}- and Mg/Ca-derived temperatures was around 14 °C from 19 to 16 ka and abruptly decreased to around 5 °C from 16 to 13 ka. This suggests a strong winter cooling of the surface water during the last glacial period. TEX^-_{86}, $U^{K'}_{37}$-, and Mg/Ca-derived temperatures were lowest at 18–17 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.

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, 2001; Shieh et al., 1997; Ujiié and Ujiié, 1999, 2006; Xu and Oda, 1999; 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, 2003; Ahagon et al., 1993; Ujiié and Ujiié, 1999), 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 1–3 °C in the central Okinawa Trough (Li et al., 2001; Sun et al., 2005; Zhao et al., 2005, 2007; Chang et al., 2008; Chen et al., 2010) and 4–6 °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

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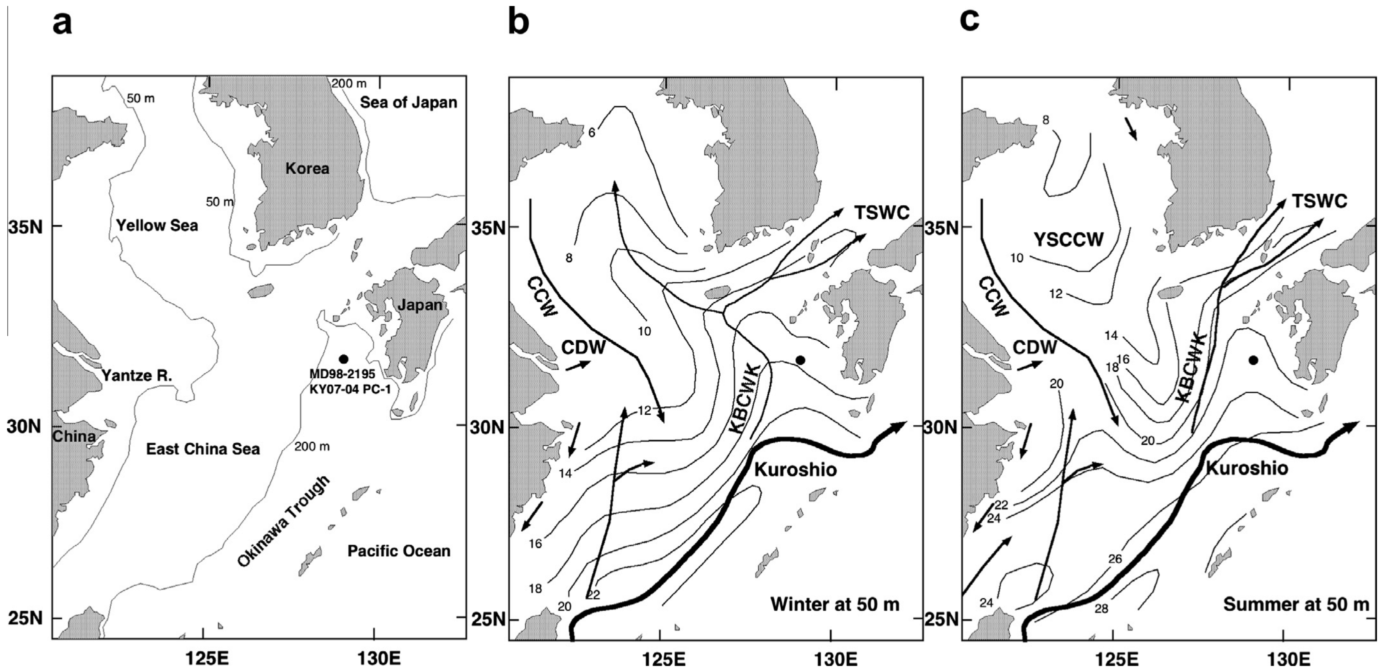

Fig. 1. (a) MD98-2195 core location, (b and c) the distribution of seasonal mean winter and summer temperatures at 50 m depth, and the surface water circulation pattern in the East China Sea and the Yellow Sea (Kondo, 1985). KSW = Kuroshio Water. CDW = Changjiang Diluted Water. CCW = Chinese Coastal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

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 $U_{37}^{K'}$-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 Scienceb), 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 m 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 15.28–15.30 m depth