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Solar forcing of centennial-scale East Asian winter monsoon variability in the mid- to late Holocene

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ABSTRACT

Centennial-scale variability of the East Asian winter monsoon during the Holocene is poorly understood because suitable archives and proxies are lacking. Here we present a high-resolution (∼30-yr spacing) planktonic foraminiferal $\delta^{18}O$ record of *Neogloboquadrina incompta* (dextral form), which reflects sea surface temperature during the winter season, for the last 6000 yrs from marine sediments in the western North Pacific. Stronger winter monsoons indicated by cooler winter SSTs correspond to weaker summer monsoons indicated by the cave oxygen isotopes in centennial-scale variability. The variability also shows good correlation with $\delta^{18}O$ records in lake sediments and ice cores from the Yukon Territory, Canada, spanning the last 4500 yrs, suggesting east–west climate coupling across the North Pacific. Furthermore, the climate changes across the North Pacific co-vary over widespread regions, such as the eastern tropical Pacific and the northern Red Sea, and the reconstructed solar activity. The cross-spectral and wavelet analyses show that the East Asian winter monsoon shares some cyclicity with the solar variability. Our results suggest that the solar activity is a fundamental forcing producing the centennial-scale EAWM variability mediated by the large-scale climate linkages.

1. Introduction

Climate during the Holocene has been relatively warm and stable compared to the last glacial period, as shown, for example, in the $\delta^{18}O$ records of Greenland ice cores (e.g., Dansgaard et al., 1993). However, with the accumulation of more paleoclimate records, it seems that the Holocene climate has not been as stable as previously thought. The repeated advances and recessions of mountain glaciers (Denton and Karlén, 1973) or the periodic occurrences of ice-rafted debris in the marine sediments (Bond et al., 1997), for instance, indicate frequent perturbations in Holocene climate. Compilations of these paleoclimate records have revealed that several climate events occurred synchronously over widespread areas and, in other cases, have revealed regional differences in climatic responses (Mayewski et al., 2004; Wanner et al., 2011). The increasingly wide spatiotemporal distribution of such records has shed light on the importance of climate modes similar to modern ones, such as the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) and El Niño–Southern Oscillation (ENSO), on much longer timescales (e.g., Marchitto et al., 2010; Rimbu et al., 2004). However, little is known about the relationship of the western North Pacific to those climate modes because of the lack of high-resolution Holocene records from the region.

The climate in East Asia is strongly influenced by the East Asian monsoon (EAM) system. Past variability of the East Asian summer monsoon (EASM) during the Holocene has been investigated by many studies using $\delta^{18}O$ in Chinese cave stalagmites (e.g., Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). Conversely, records of the East Asian winter monsoon (EAWM) are sparse owing to the limited number of suitable archives and proxies. Although the grain size of Chinese loess is a classic proxy of the EAWM (e.g., Porter and An, 1995), it gives typically only low-resolution records and there are several uncertainties regarding sedimentary process (Stevens et al., 2007). Such factors hinder the reconstruction of high-resolution Holocene records. The covariance between the EASM and EAWM is an interesting aspect of the EAM system because it seems to change depending on the time and/or timescales.

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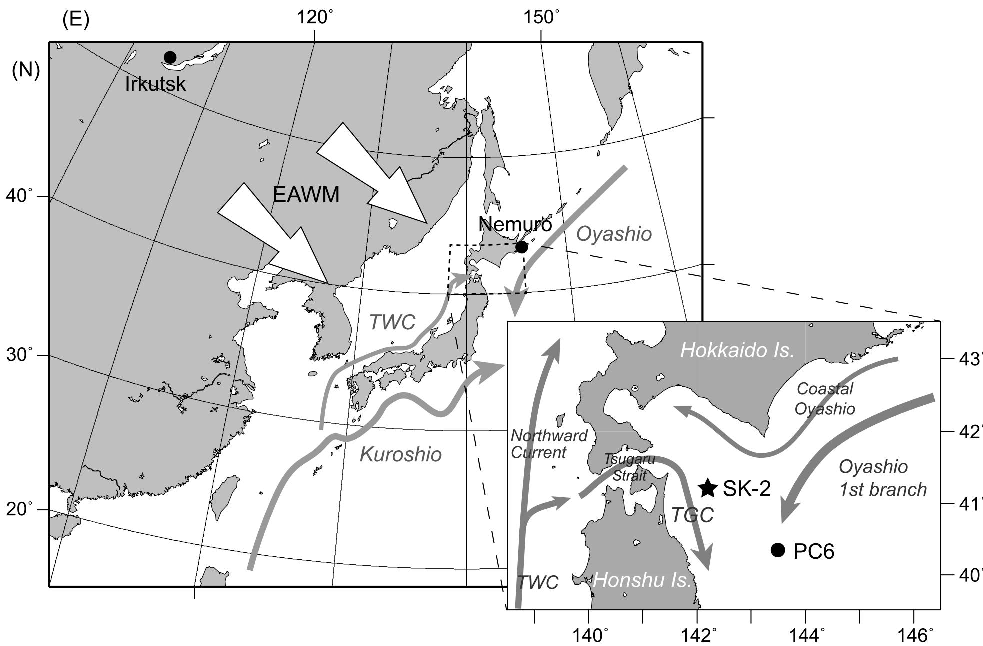

Fig. 1. Maps showing the study region in the western North Pacific and surface current system around the region (gray arrows). The enlarged view shows the locations of the core site SK-2 and a reference site PC6 (40°24′N, 143°30′E) (Minoshima et al., 2007). TWC: Tsushima Warm Current, TGC: Tsugaru Warm Current.

Variations are inversely related on glacial/interglacial (e.g., Wang et al., 1999) and millennial time scales during the last glacial period (Sun et al., 2012), whereas Holocene millennial records suggest an in-phase relationship (Steinke et al., 2011). Liu et al. (2009) reported seasonally inverse variations of the Asian monsoon for the last 3800 yrs using lake sediments from the Qinghai–Tibetan Plateau. Since the proxies they used are possibly affected by both seasons, the seasonal signals in the records could not be technically separated. Therefore, a high-resolution proxy record that properly reflects a winter climate signal is needed to investigate centennial-scale winter monsoon variability and its relationship to the summer monsoon.

The $\delta^{18}O$ of planktonic foraminiferal shells in marine sediment is a reliable proxy for past surface ocean changes. One of the great advantages of using foraminiferal shells is that, if we understand the modern seasonal preference of different foraminiferal species, we can obtain paleoceanographic information from a specific season. In this study, we analyzed the $\delta^{18}O$ of the planktonic foraminifer *Neogloboquadrina incompta* (dextral form), whose shell flux shows a maximum in winter at the study site (Sagawa et al., 2013). A core with a high sedimentation rate (SK-2: average sedimentation rate = ∼77 cm/kyr) retrieved from the northwestern margin of the North Pacific (Fig. 1) enabled us to generate a high-resolution (∼30-yr spacing on average) $\delta^{18}O$ record, which reflects the strength of the EAWM. A comparison of our record with $\delta^{18}O$ records from Chinese cave and lake sediment and mountain glacier core from the Yukon, Canada, reveals that the centennial-scale EAWM variability is strongly related to the EASM and large-scale atmospheric circulation in the Northern Hemisphere. It is also proposed that the fundamental forcing of those variations could be perturbations of solar activity.

2. Oceanographic and meteorological settings

The surface current system around the study site is characterized by two local currents with different properties: the Oyashio Current (OY) and the Tsugaru Warm Current (TGC) (Fig. 1). The OY is a western boundary current of the Western Subarctic Gyre of the North Pacific that transports cold, relatively less saline surface water [<7 °C and 33.0–33.7 Hanawa and Mitsudera, 1986] from high latitudes. The OY off the southeastern coast of Hokkaido Island, Japan, bifurcates into the first branch of the OY and the coastal Oyashio Water (Kono et al., 2004). The first branch of the OY reaches its southernmost latitude in late winter to early spring and its northernmost latitude in late summer to autumn (Yasuda, 2003). The TGC consists of water whose temperature is warmer than 5 °C and salinity is 33.7–34.2 (Hanawa and Mitsudera, 1986), and it originates from the Tsushima Warm Current (TWC). The volume transport of the TGC has been estimated at ∼1.5 ± 0.5 Sv with little interannual variation (Ito et al., 2003; Onishi and Ohtani, 1997). The influence of the TGC on the northeast coast of Honshu Island, Japan, increases in summer and autumn, and the TGC water prevails in the region until early winter (Hanawa and Mitsudera, 1986). Seasonal temperature variations of 2.5–16.1 °C and salinity variations of 33.15–33.75 have been reported at 30 m water depth in the World Ocean Atlas 2009 (Antonov et al., 2010; Locarnini et al., 2010).

The sea surface temperature (SST) record of the studied region in winter (three months average from December to February) shows interannual variations with an average of 8.9 ± 1.1 °C for the last ∼50 yrs (Carton and Giese, 2008) (Fig. 2a). Relatively cold SSTs were observed in the mid-1970s and mid-1980s. Winter SSTs in the northwestern North Pacific are largely constrained by the strength of the northwesterly wind of the EAWM (Hanawa et al., 1989), driven by the sea level pressure (SLP) difference between the Siberian high (SH) and the Aleutian low (AL). This is supported by the negative correlation ($r = -0.51$ for 1970–2006; Table 1) between wintertime SSTs and the monsoon index (MOI), which is the SLP difference between Irkutsk, Russia, and Nemuro, Japan (Hanawa et al., 1988) (Figs. 1, 2a and 2b). The SSTs also represent decadal-scale changes showing gradual cooling from 1960 to the mid-1980s and the subsequent recovery during the late 1980s. Similar changes have been observed in the Pacific Decadal Oscillation (PDO) index (Mantua et al., 1997), and the correlation coefficient is −0.56 (Table 1 and Fig. 2c), indicating that decadal-scale SST variability is closely related to the temperature distribution pattern in the entire North Pacific (Minobe, 1997). It is also noteworthy that the AO seems to be associated with the MOI and the North Pacific temperature changes ($r = -0.56$ and 0.46 with MOI and SST, respectively; Table 1 and Fig. 2d). The AO/NAO repre-