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Reconstruction of winter monsoon strength by elemental ratio of sediments in the East China Sea

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ABSTRACT

The East Asian winter monsoon (EAWM) transports cold air from the high northern latitudes to the mid- and low-latitudes. Thus investigations on its variation pattern and mechanism are essential for acquiring further knowledge on the interplay across the high and low latitudes. Proxies such as grain size and foraminiferal $\delta^{18}O$ in marine sediments and elemental ratios in the Chinese loess have been used for the reconstruction of EAWM strength. However, more high-resolution reconstructions for EAWM are required for further understanding the mechanism of climate systems and predicting climate change. In this study, we present a high-resolution time-series of the late Holocene EAWM strength reconstructed by element method. Comparisons of element concentrations, elemental ratios and mean grain size (MGS) of environment-sensitive components in a sediment core from the shelf of the East China Sea indicate that K/Ti ratio is an appropriate proxy for the reconstruction of the EAWM strength. K/Ti ratio exhibits similar trends with proxies of sea surface temperature and EAWM strength in different regions influenced by the EAWM. Warm and cold periods such as the Roman Warm Period, Medieval Warm Period and Little Ice Age are identified in the reconstructed results. Total solar irradiance anomaly (ΔTSI) and K/Ti ratios exhibit comparable tendencies in the last two millennia and frequency spectrum analysis exhibits similar periodicities in the time series of ΔTSI and K/Ti, which confirm that solar irradiance has a significant impact on the EASM on centennial time scale.

1. Introduction

The East Asian monsoon (EAM), consisting of the East Asian summer monsoon (EASM) and the East Asian winter monsoon (EAWM), plays a significant role in the climate process of East Asia. It exerts direct impact on the temperature and precipitation in this region, and consequently influences the occurrence of extreme climate events and disasters, e.g. floods and severe cold winters (Wang et al., 2005a). Due to the interplay among regional climate systems, the EAM, part of the global climate system, also influences the global climate significantly (An, 2000). Thus, it is of critical importance to investigate the evolution and driving mechanism of the EAM.

Grain size and magnetic susceptibility of the Chinese loess are common proxies for the reconstruction of EAWM and EASM evolutions on tectonic and orbital time scales (An et al., 1991; Liu and Ding, 1998; Xiao et al., 1995). However, owing to the low sedimentation rate, they are incapable of high-resolution reconstructions on millennial or centennial time scales. On the contrary, proxies in archives such as lacustrine sediments (Gasse et al., 1991; Huang et al., 1997; Ji et al., 2005; Yancheva et al., 2007), speleothem (Dykoski et al., 2005; Tan et al., 2003), tree ring (Feng et al., 1999; Treydte et al., 2006) and peat bog (Hong et al., 2001; Zhou et al., 1996) are often used to study high-resolution climate variations.

Large areas of muddy sediments are distributed on the coastal continental shelf of China. These regions are under the influence of monsoonal climate, therefore the muddy sediments are good materials for studying monsoon evolution. Proxies used for the reconstruction of paleoclimate include MGS and contents of environment-sensitive components (Liu et al., 2010; Xiang et al., 2006; Xiao et al., 2006; Zhou et al., 2014), contents and grain size of specific minerals (Qiao et al., 2011), foraminiferal oxygen isotopes (Xiang et al., 2009), and organic geochemical proxies such as $U^{K'}_{37}$ and TEX_{86} (Kong et al., 2014; Li et al., 2009; Nakanishi et al., 2012; Xing et al., 2013). Previous studies have suggested that the MGS of environment-sensitive components in mud sediments of the Yellow Sea and the East China Sea can be used to reconstruct the

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EAWM strength in the Holocene (Hu et al., 2012; Liu et al., 2010; Xiang et al., 2006; Xiao et al., 2006). A high MGS represents strong EAWM and a low one represents weak EAWM. The interpretation of this relationship is that variations in the EAWM strength alter the sediment dynamics of suspended materials and consequently the frequency distribution of the sediments grain size. Zhou et al. (2014) studied five MGS-derived time series of EAWM for the last two millennia and found that the EAWM trends in some periods of the last two millennia were different or even opposite. They attributed the discrepancies to the differences in grain size-standard deviation variation curves of the sediments and to direct material input from river estuary. The discrepancies in different reconstructed results suggest that more high-resolution reconstructions based on various types of proxies are required to study the EAWM strength variations.

Element method has been used in numerous studies on the monsoonal evolution process. The Ti/Al ratio was used as proxy for the Indian Southwest Monsoon (Reichart et al., 1997; Shimmield et al., 1990) in Arabian Sea. Ba/Sr and Th/U ratios in the loess-paleosol sequence might be used as chemical indicators of paleoclimatic change (Gallet et al., 1996). Rb/Sr ratio and FeD/FeT index in the Chinese loess sequences both revealed variations of EASM in the Quaternary (Chen et al., 1999a, b; Guo et al., 2000). Changes of the EAWM have also been revealed by Zr/Rb ratio in the Chinese loess (Chen et al., 2006; Liu et al., 2002, 2004, 2006). However, high-resolution reconstructions of EAWM in mid- to late-Holocene based on elemental ratios are relatively sparse. Using the environment-sensitive grain size, clay mineral and major element assemblages in a sediment core from the mud area on the inner shelf of the East China Sea, Liu et al. (2010) reconstructed the EAWM history since the mid-Holocene and identified 10 cold events and 4 stages of EAWM strength change. Xie et al. (2014) studied the climate change since MIS 3 by K/Ti ratio and grain size derived from northern South China Sea sediments and found a close correlation between variations in K/Ti ratio and grain size of fine fraction. Wei et al. (2004) investigated the concentrations of major and trace elements and their Ti-standardized ratios in ODP 1144 core drilled in northern South China Sea. They concluded that the elemental variation patterns were indicative of wet and warm climate, which resulted from enhanced summer monsoon during interglacials and dry climate caused by strengthened winter monsoon in glacials, in South China.

Therefore, more high-resolution reconstructions of the EAWM for the late Holocene are required for understanding the climate change. In this study, we analyzed the major element concentrations and ratios in a sediment core from the East China Sea, and reconstructed the EAWM strength for the past 2000 years. Here we report and compare our results with reconstructed sequences from previous studies and discuss the evolution history of the EAWM, solar forcing of the EAWM, and its centennial-scale impact on climate change.

2. Study area

Large amount of materials are transported to the shelf sea of China from the Yangtze River estuary, the Yellow River estuary, and the submerged old Yellow River delta every year. These materials, suspending in water when transported by currents, are the major source of the coastal muddy sediments (Milliman et al., 1985a, b). The transport processes are distinctly seasonal, i.e. deposited in summer and transported in winter (Sun et al., 2000; Yang et al., 1992). In summer, the subsurface and intermediate water of the Kuroshio Current flows upward to the continental shelf along the continental slope and thus forms a vertically distributed "water barrier" along the transitional region between the shelf and shelf slope. This barrier is of lower concentration of suspended materials (<0.5 mg/dm^3) compared with the adjacent waters (1–50 mg/dm^3). It blocks the transport of middle and lower layers of the shelf sea water, which contains large quantity of suspended materials, to the deep sea. The barrier effect reaches its peak in September. In winter, the climbing current retreats to the shelf break (150 m in depth approximately) and the "water barrier" disappears. As a result, the suspended materials are transported to the deep sea. This process occurs from December to next April. During this period, the shelf sediments, already deposited in summer, resuspend because of the vertical mixing effect caused by the EAWM and are transported away by current (Yang et al., 1992).

Part of the estuary and delta input materials are transported southward by the Min-Zhe Coastal Current and deposited on the southeast continental shelf of China to form the Min-Zhe coastal mud area (MZCM). The mud area is formed in the past 7000 years with a total volume of 4.5×10^{11} m^3, equivalent to 5.4×10^{11} t of sediment. Thickness of the muddy sediments varies from 40 m to <1–2 m and the width is less than 100 km (Liu et al., 2007). According to the source and transport process of the materials, the muddy sediments not merely archive information on variations of river input and coastal currents, but also record winter monsoon evolution and human activity history. Thus it is possible to reconstruct the paleomonsoon strength by choosing proper proxies in the muddy sediments.

3. Materials and methods

A sediment core, T08-A, was retrieved from the northern part of MZCM (122°28′E, 28°30′N) by gravity corer in 2011 on the research vessel Dong Fang Hong 2 (Fig. 1). The water depth of the core site was 64.6 m. The 220-cm-long core was grey and mainly consisted of clayey silt. We sliced the core into 1-cm-thick pieces on the vessel and obtained 220 subsamples. The upper 30 cm section was discarded due to the disturbance by the corer.

Element concentrations and grain size of all the subsamples were analyzed. The element concentrations were determined using an X-ray fluorescence (XRF) spectrometer (Axios^{mAX}-Minerals, PANalytical B.V.) by fusion method. Air dried sediments were ground into powder with particle size equivalent to that of powder sieved by No. 200 (75 μm) mesh. 0.7000 ± 0.0003 g of sample and 7.0000 ± 0.0003 g of lithium borate, both were dried and stored in a glass desiccator before determination, were mixed uniformly and fused into a glass piece. Then the sample pieces were tested in the spectrometer (Rh-anode as X-ray tube) with a relative error of 0.1–1.0%. The element analysis was performed in Institute of Geology and Geophysics, China Academy of Sciences.

The methods for grain size analysis and calculation of the MGS of environment-sensitive components were reported in our previous study (Zhou et al., 2014). Three sedimentary components with mean grain size ranges of 0.4–3, 3–30 and 63–282 μm were identified according to the grain size-standard deviation curve, and the component of 3–30 μm was determined as the environment-sensitive components based on variations in the mean grain sizes and contents of the three components (Zhou et al., 2014).

Benthic foraminifera of various species were used for AMS ^{14}C dating. The result was calibrated to calendar age by Calib 6.1.1 (Stuiver and Reimer, 1993) and the Marine04 calibration dataset (Hughen et al., 2004) was used. A regional difference from the average global marine reservoir correction (ΔR) of −128 ± 35 years was obtained from the online ^{14}CHRONO Marine Reservoir Database (http://www.calib.qub.ac.uk/marine). We chose No. 416 (36.1°N, 120.3°E, ΔR = −81 ± 60), 417 (36°N, 126.3°E, ΔR = −111 ± 45) and 418 (34.7°N, 128.2°E, ΔR = −154 ± 35)