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Low-high latitude interaction forcing on the evolution of the 400 kyr cycle in East Asian winter monsoon records during the last 2.8 Myr

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ABSTRACT

Variability of the East Asian winter monsoon (EAWM), stronger during glacials and weaker during interglacials, has been tightly linked to the wax and wane of the Northern Hemisphere ice sheets (NHIS) via the Siberian High over the last 2.8 million years (Myr). However, the long eccentricity cycle (ca. 400 kyr) in the EAWM record from the late Pliocene to early-Pleistocene (2.8–1.2 Ma) could not be linked to NHIS changes, which lacked the long eccentricity cycle in the Pleistocene. Here, we present the first low latitude EAWM record of the last 2.8 Myr using surface and subsurface temperature difference from the northern South China Sea to evaluate interactions between tropical ocean and EAWM changes. The results show that the EAWM variability displayed significant 400 kyr cycle between 2.8 Ma and 1.2 Ma, with weak (strong) EAWM during high (low) earth orbital eccentricity state. A super El Niño–Southern Oscillation (ENSO) proxy record, calculated using west-east equatorial Pacific sea surface temperature differences, revealed 400 kyr cycles throughout the last 2.8 Myr with warm phase during high eccentricity state. Thus, we propose that super ENSO mean state strongly modulated the EAWM strength through remote forcing to generate the 400 kyr cycle between 2.8 Ma and 1.2 Ma, while low NHIS volume was not sufficient to dominate the EAWM variation as it did over the last 0.9 Myr with 100 kyr cycles in dominance.

1. Introduction

The East Asian winter monsoon (EAWM) transports high latitude climate signal to subtropical and tropical regions, and it influences climate and environments from eastern Asia/Russia to the subtropical western Pacific Ocean (An, 2000; Webster et al., 1998). Thus, understanding mechanisms controlling EAWM variations in the past is fundamentally important for predicting global and regional climate changes under global warming conditions (Maher, 2016). Quartz mean grain size (QMGS) records from the Chinese Loess Plateau revealed that the EAWM displayed glacial-interglacial oscillations, e.g. 41 kyr and 100 kyr cycles during the past 2.8 million years (Myr), as well as a long eccentricity cycle of ca. 400 kyr for the 2.6–1.2 Ma interval (Sun et al., 2006). During the middle-late Pleistocene (0.9–0 Ma), periodicities of 100 kyr in the EAWM record paced with the rhythm of Northern Hemisphere ice sheets (NHIS) represented by the benthic foraminiferal $\delta^{18}O$ record ($\delta^{18}O_b$) (Lisiecki and Raymo, 2005; Sun et al., 2006), rather than with periodicities of 41 kyr and 23 kyr of north high latitude winter season insolation (Laskar et al., 1993). This suggested that the evolution of the EAWM was controlled by NHIS on orbital time scales (Sun et al., 2006), however there were differences. First, the EAWM record lacked the “saw-tooth” shape in the $\delta^{18}O_b$ curve (Ding et al., 1995; Hao et al., 2012); and more significantly, the strong 400 kyr cycle in the EAWM record was absent or negligible in the NHIS (Lisiecki and Raymo, 2005). Thus, the evolution of EAWM was likely affected by other factors in addition to the NHIS volume changes since the onset of significant northern hemispheric glaciations, ca. 2.7 million years ago (Haug et al., 2005). On the other hand, the 400 kyr cycle has been found in many tropical and subtropical paleorecords (Bard and Rickaby, 2009; Herbert et al., 2010; Liu et al., 2008; Rickaby et al., 2007; Tiedemann et al., 1994), forced by several mechanisms related to tropical insolation (Ashkenazy and

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Gildor, 2008; Berger et al., 2006). Local winter insolation forcing was also used to explain the existence of 400 kyr cycle in EAWM record between 2.6 and 1.2 Ma (Sun et al., 2006), but no plausible explanation has been proposed for the lack of 400 kyr cycle for the last 1.2 Myr. It is likely that low-high latitude interaction is required for the evolution of the 400 kyr cyclicity in the EAWM affected regions.

The South China Sea (SCS) climate records could be ideal candidate to test low-high latitude interactions as previous studies have demonstrate that sea surface temperature (SST) changes were mainly forced by monsoon climate over a range of timescales (Li et al., 2013; Shintani et al., 2008; Tian et al., 2005), but could also be influenced by low latitude climate due to its unique geographical location between the Asian continent and the tropical western Pacific Ocean. SST of modern SCS is sensitive to both El Niño–Southern Oscillation (ENSO) and EAWM and their interactions (Chen et al., 2015; Wu et al., 2014), through the Philippine Sea lower-tropospheric anticyclonic/cyclonic anomalies (Wang et al., 2000, 2010). During warm ENSO period, western Pacific cooling and synchronous central-eastern Pacific warming induced an anomalous lower-tropospheric anticyclone over the Philippine Sea, which further reduced EAWM intensity (Wang et al., 2000, 2010). However, previous studies focused on short timescale links (Wang et al., 2012; Zheng et al., 2014), limiting our knowledge about the interaction between EAWM and tropical climate mean state during the Quaternary. In this study, we compare EAWM and equatorial Pacific super ENSO records for the last 2.8 Myr to investigate the relationship between EAWM and tropical climate state. The EAWM record of the past 2.8 Myr is generated by vertical temperature gradient ($\Delta T_{\mathrm{vertical}}$) using new surface and subsurface temperature records from ODP Site 1147/48 in the northern SCS (Fig. 1); while the super ENSO record is represented by zonal SST difference ($\Delta T_{\mathrm{W-E}}$) between western and eastern equatorial Pacific using published SST records (de Garidel-Thoron et al., 2005; Lawrence et al., 2006; Li et al., 2011; Medina-Elizalde and Lea, 2005). Our results suggest tight correlation between EAWM and Pacific super ENSO climate state on the 400 kyr cycle during 2.6–1.2 Ma interval.

2. Oceanographic setting

The SCS lies in the tropical region with the East Asian monsoon prevailing. During the boreal summer, southwest warm wind drives intrusion of warmer Indian Ocean water through the Sunda Shelf resulting in homogeneously high SST (~29 °C) in the whole SCS basin (Wang and Li, 2009). While under the influence of northeast winter monsoon wind, SST drops to 20–23 °C in the northern SCS and to about 27 °C in the southern SCS (Wang and Li, 2009). Besides seasonal SST variability, upper water vertical thermal gradient in the northern SCS is also sensitive to monsoon forcing. Stronger winter wind stirs the upper water resulting in deeper mixed layer depth (MLD) and smaller vertical thermal gradient (Fig. 2). As show in Fig. 2b, temperature difference between surface and subsurface waters (i.e., $\Delta T = T_{(0-30\ \mathrm{m})} - T_{(50-100\ \mathrm{m})}$) of winter season displays a negative correlation with MLD in the northern SCS.

3. Material and methods

3.1. Samples and age model

ODP Site 1148 (18°50.167′N, 116°33.939′E; water depth of 3296 m) was drilled in the lower continental slope from the northern SCS (Tian et al., 2008). ODP Site 1147 (18°50.11′N, 116°33.28′E; water depth of 3245 m) was a short core recovered only 1.16 km away from ODP Site 1148. In this study, ODP Site 1147/48 records were constructed by combining the upper 46.91 mcd (meters composite depth) of ODP Site 1147 and 47.61–151.53 mcd from ODP Site 1148 (Fig. 1). Sediment samples were taken at ca. 50 cm interval in this study, generating an averaged resolution of ca. 9.0 kyr per sample spanning the last 2.8 Myr based on the age model provided by Tian et al. (2008).

3.2. Alkenone analysis and $U^{K'}_{37}$ temperature calculation

Sample pre-treatment for alkenone analysis was carried out according to the procedures described by Li et al. (2013). Freeze-dried samples (2–4 g) were ultrasonically extracted (15 min each time) with a mixture of dichloromethane and methanol for 4 times. After hydrolyzed in a KOH-methanol solution, extracts were separated into polar and apolar fractions using silica gel chromatography. The polar fraction was derivatized with *N,O*-bis(trimethylsilyl)trifluoroacetamide at 70 °C for 2 h. Alkenone identification was performed on a Thermo gas chromatograph–mass spectrometer (GC-MS) using an HP-1 column (50 m × 0.32 μm × 0.17 μm). The GC oven temperature program is: temperature was started from 80 °C and kept for 1 min, and then increased to 200 °C at a rate of 25 °C min^{-1}, then followed by three steps of increase at 4 °C min^{-1} to 250 °C, at 1.7 °C min^{-1} to 300 °C (holding for 10 min), and at 5 °C min^{-1} to 310 °C (holding for 8 min). $U^{K'}_{37}$ is calculated using equation proposed by Prahl and Wakeham (1987) and is converted into SST by using the global linear calibration equation (Müller et al., 1998): SST (°C) = ($U^{K'}_{37}$ −0.044)/0.033. Duplicate measurements resulted in a precision better than 0.3 °C for $U^{K'}_{37}$ SST in our laboratory.

3.3. Thaumarchaeotal lipid analysis and TEX^{H}_{86} temperature calculation

Glycerol dibiphytanyl glycerol tetraethers (GDGTs) were extracted from sediment according to the procedures described by Li et al. (2013). In general, freeze-dried sediments (2–4 g) were ultrasonically extracted (15 min each time) 3 times with methanol, 3 times with dichloromethane:methanol (v:v = 1:1), and 3 times with dichloromethane. Salts and water were removed by passing combined extracts through a Na_2SO_4 column. Polar fraction, which contains GDGTs, was acquired by passing total extracts through column chromatography with activated Al_2O_3 using dichloromethane:methanol (v:v = 1:1) as eluent. Agilent 1200 HPLC coupled to a Waters Micromass-Quattro Ultima™ Pt mass spectrometer with an APCI probe was used for GDGTs analysis. A Prevail Cyano Column (150 × 2.1 mm, 3 μm) is maintained at 30.0 °C, and elution program are as follows: column chromatography is eluted isocratically first using hexane/isopropanol (v:v = 99:1) for 3 min, then using a linear gradient up to 2.4% of isopropanol over 25 min, with a constant flow rate of 0.2 ml min^{-1}. In order to clean column, back flushing is carried out with hexane/propanol (v:v = 99:1) at 0.2 ml min^{-1} for 10 min after each sample analysis. Parameters for APCI/MS are as following: source temperature at 95 °C, corona at 6.0 μA, APCI probe temperature at 550 °C, desolvation N_2 gas flow at 600 L h^{-1}. Selected Ion Recording (SIR) is used to scan the $[M+H]^+$ ions of the branched and isoprenoid GDGTs with a dwell time of 237 ms for each ion.

TEX^{H}_{86} is calculated using equation proposed by Kim et al. (2010). TEX^{H}_{86} value is converted to temperature using the regional empirical equation of the SCS (Jia et al., 2012): $T(°C) = 54.5 \times TEX^{H}_{86} + 30.7$. Duplicate analytical accuracy for TEX^{H}_{86} temperature was better than 0.5 °C in our lab. The relative contents of branched GDGTs and crenarchaeol were used to calculate the Branched and Isoprenoid Tetraether (BIT) index for