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

Dawei Li a, b, c, Meixun Zhao a, b, *, Jun Tian d

a Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China
b Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China
c State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 36102, China
d State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

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A B S T R A C T

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 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 δ18O record (δ18Oe) (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 δ18Oe 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 paleo-records (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
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 Nino–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 ($\Delta T_{\text{vertical}}$) 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 temperature records from ODP Site 1147/48 in the northern SCS (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 $U_{\text{14C}}^{15}$ temperature calculation

Sample pre-treatment for alkenone analysis was carried out according to the procedures described by Li et al. (2013). Freezedried samples (2–4 g) were ultrasonically extracted (15 min each time) with a mixture of dichloromethane and methyl alcohol 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). $U_{\text{14C}}^{15}$ 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) = ($U_{\text{14C}}^{15}$ −0.044)/0.033. Duplicate measurements resulted in a precision better than 0.3 °C for $U_{\text{14C}}^{15}$ SST in our laboratory.

3.3. Thaumarchaeotal lipid analysis and $\text{TEX}_{\text{13C}}$ 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 Na2SO4 column. Polar fraction, which contains GDGTs, was acquired by passing total extracts through a Na2SO4 column. Parallel fraction, which contains DGTS, was acquired by passing total extracts through column chromatography with activated Al2O3 using dichloromethane:methanol (v:v = 1:1) as eluent. Agilent 1200 HPLC coupled to a Waters Micromass–Quattro Ultima™ Pt mass spectrometer with an APCl probe was used for GDGTs analysis. A Prevail Cyanos 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 APCl/MS are as following: source temperature at 95 °C, corona at 60.0 µA, APCl probe temperature at 550 °C, desolvation N2 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.

$\text{TEX}_{\text{13C}}$ is calculated using equation proposed by Kim et al. (2010). $\text{TEX}_{\text{13C}}$ value is converted to temperature using the regional empirical equation of the SCS (Jia et al., 2012): $T(°C) = 54.5 × \text{TEX}_{\text{13C}} + 30.7$. Duplicate analytical accuracy for $\text{TEX}_{\text{13C}}$ 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...
further evaluating the bias of terrestrial isoprenoid GDGTs input on the TEX$_{86}^{11}$ index (Weijers et al., 2006b).

### 3.4. Interpretation of temperature proxies in the SCS

TEX$_{86}^{11}$ index reflects annual mean mixed layer temperature in the northern SCS. Haptophytes, organisms producing alkenones for calculating UC$_{37}$, favor strong sunlight and grow under oligotrophic nutrient condition in the upper euphotic zone (Houghton, 1988; Loebi et al., 2010; Mitchell-Innes and Winter, 1987; Nanninga and Tyrrell, 1996). Under the influence of EAWM, haptophyte productivity displays moderate winter season bias in the northern SCS (Chen, 2005; Chen et al., 2007); however, Pelejero and Grimalt (1997) found that the UC$_{37}$ index reflected annual mean temperature of the upper mixed layer (0–30 m), and this was further supported by a recent study carried out by Jia et al. (2012). One explanation is the “time averaging effect”, which homogenized seasonality during particle descending (Hwang et al., 2014).

TEX$_{86}^{11}$ index reflects subsurface water temperature. Although TEX$_{86}^{11}$ is calibrated against annual mean SST when it was proposed (Schouten et al., 2002), it has been reported to be a robust proxy for subsurface water temperature in subsequent studies (Ho and Laepple, 2016; Jia et al., 2012; Kim et al., 2012; McClaymont et al., 2012). Thaumarchaeota participates in nitrification process (Beman et al., 2008; Köneke et al., 2005; Martens-Habbena et al., 2009), and they can grow chemolithoautotrophically by aerobically oxidizing ammonia, which predominantly displays maximum concentration in the depth of chlorophyll a maximum of the euphotic zone (Herndl et al., 2005; Wuchter et al., 2003). This metabolism leads to the deeper habitat of thaumarchaeota compared to haptophytes. Although there is insufficient data from the SCS to assess the seasonal productivity of the thaumarchaeota, TEX$_{86}^{11}$ values of deep water sediment trap samples from other regions have been reported to reflect annual mean water temperature rather than thaumarchaeota blooming season temperature (McClymont et al., 2012; Wuchter et al., 2005). Similar to the UC$_{37}$ index, the homogenization process during the transportation of GDGTs from euphotic zone to deep water column can weaken the seasonal temperature signal recorded in the TEX$_{86}^{11}$ index (Wuchter et al., 2006). As for the SCS, surface sedimentary TEX$_{86}^{11}$ values exhibit the strongest correlation with annual mean rather than seasonal water temperatures at 75 m (Jia et al., 2012), which is
equivalent to the integrated depth of chlorophyll a maximum in the northern SCS basin (Liu et al., 2002).

4. Results and discussions

4.1. Evaluating influence of terrestrial isoprenoid GDGTs on the TEX$_{86}$ index

Due to the presence of isoprenoid GDGTs in soils (Weijers et al., 2006b) and peat bogs (Weijers et al., 2006a), marine TEX$_{86}$ signal could be biased by sufficient input of terrestrial isoprenoid GDGTs through fluvial transportation, especially for sites near large river outflows. The BIT index is a proxy for evaluating the effect of terrestrial isoprenoid GDGTs on TEX$_{86}$ index (Weijers et al., 2006b). BIT values in our samples ranged from 0.034 to 0.423, with most values below 0.2 (Fig. 3), suggesting negligible terrestrial effect on marine TEX$_{86}$ temperature signal (Weijers et al., 2006b).

4.2. Temperature records from the northern SCS

The U$_T^{K}$ index has been applied widely in reconstructing long-term SST for both open oceans and marginal seas (Fedorov et al., 2015; Herbert et al., 2010, 2016; Lawrence et al., 2006, 2009; Li et al., 2011), and it has been interpreted as a valid proxy reflecting annual mean SST in the northern SCS (see section 3.4 for details). U$_T^{K}$ SST from ODP Site 1147/48 was in the range of 22.3–28.0 °C, while displaying a long-term cooling trend that decreased gradually from 27.6 °C (average) in the late Pliocene to ca. 24.6 °C in middle-late Pleistocene (Fig. 4c). Evolutional spectral analysis of this record reveals that the 41 kyr cycle dominated from ca. 1.7 Ma to ca. 0.5 Ma, and the 100 kyr cycle appeared at ca. 0.7 Ma and was amplified over the last 0.7 Myr (Fig. 5b). The evolution of the 41 kyr and 100 kyr cycles in SST from ODP Site 1147/48 is similar to that of global ocean benthic foraminiferal $\delta^{18}$O stack ($\delta^{18}$O stack) record (Lisiecki and Raymo, 2005) (Fig. 5a), suggesting a tightly coupled relationship between SCS SST and high latitude climate changes through the EAWM teleconnection. However, sample resolution of ODP Site 1147/48 is ca. 9.0 kyr on average, which is about 3–4 times larger than the reported phase lead/lag of tropical SST relative to $\delta^{18}$O$_{O}$ (Herbert et al., 2010; Lawrence et al., 2006), thus it is not suitable for making phase relationship analysis for ODP Site 1147/48. Instead, we use two published high resolution SST records from the northern (ODP Site 1146; Herbert et al., 2010) and southern SCS (ODP Sites 1143) (Li et al., 2011), respectively, for phase relationship analysis. Records from both ODP Sites 1143 and 1146 have the same LR04 age model (Lisiecki and Raymo, 2005), so the results are not affected by age uncertainty among different sites. As displayed in Fig. 6, phase results show that SST from the northern SCS was tightly coupled with $\delta^{18}$O$_{O}$ from the same site (phase difference is 0.7 ± 0.9 kyr) on obliquity cyclicity during the last 1.9 Myr; whereas the SST from the southern SCS leads $\delta^{18}$O$_{O}$ (phase difference is 3.1 ± 1.5 kyr) during the last 2.5 Myr, consistent with the phenomena observed in tropical oceans, i.e. tropical SST leads $\delta^{18}$O$_{O}$ by 2–5 kyr on glacial cycles (Herbert et al., 2010; Lawrence et al., 2006, 2009). This demonstrated that SST from the northern SCS was more affected by northern high latitude climate through EAWM, whereas SST from the southern SCS was not affected.

In addition, a strong 400 kyr cycle is observed throughout the 2.8 Myr SST record of ODP Site 1147/48 (Fig. 5b and Fig. 7b). The 400 kyr cycle has also been observed in other tropical SST records, including ODP Site 1146 and 1143 from the SCS (Herbert et al., 2010; Li et al., 2011), ODP Site 846 from the eastern equatorial Pacific (Lawrence et al., 2006), ODP Site 722 from the Arabian Sea (Herbert et al., 2010), and ODP site 662 from the eastern equatorial Atlantic (Herbert et al., 2010). However, this 400 kyr cycle in SST records could not be caused by high latitude forcing because the 400 kyr cycle was absent in the NHIS record, i.e. $\delta^{18}$O$_{O}$ stack (Lisiecki and
Raymo, 2005). From the smoothed records (Fig. 7) which removed high frequent signals, similar and in-phase variations of tropical SSTs and eccentricity were observed on the 400 kyr cyclicity, with low eccentricity state pacing cooler SST state, and high eccentricity pacing warmer SST state. Annual maximum (and minimum) daily equatorial insolation is modulated by eccentricity and is characterized by pronounced 400 kyr and 100 kyr cycles (Ashkenazy and Gildor, 2008); thus evolution of tropical SST might be also modulated by low latitude climate forcings during the past 2.8 Myr.

The TEX$_{86}$ index is a subsurface temperature proxy (see section 3.4 for details). TEX$_{86}$ temperature of ODP Site 1147/48 oscillated between 15.8 °C and 22.5 °C over the last 2.8 Myr (Fig. 4d), with the 41 kyr cycle dominating between 1.8 Ma and 0.4 Ma, and the 100 kyr cycle dominating over the last 0.7 Myr (Fig. 5c). Obvious differences exist between U$_{57}^{o}$-SST and TEX$_{86}$ subsurface temperature of ODP Site 1147/48. First, the long trend of U$_{57}^{o}$-SST decreased...
gradually from about 2.8 Ma to about 0.9 Ma, accompanying by a gradual amplification of temperature variability (Fig. 4c); whereas subsurface temperature, i.e. TEXH, temperature, was relatively stable between 2.8 Ma and 2.0 Ma (Fig. 4d), and then it decreased gradually until ca. 0.7 Ma. In addition, the glacial-interglacial amplitude of subsurface temperature oscillation was relatively stable between 2.8 and 1.2 Ma, but was larger during the last 1.2 Myr. Second, the 400 kyr eccentricity cycle was not observed in the subsurface temperature record but it existed in the SST record during the past 2.8 Myr (Figs. 5 and 7). These differences suggest subsurface temperature from the northern SCS is more tightly linked with high latitude climate signal which could be transported by deep water circulation to low latitudes (Fedorov et al., 2006; Philander and Fedorov, 2003). This link is evident in the comparison of the TEXH and δ18O records from the same core (Figs. 4 and 7c), revealing similar glacial-interglacial oscillations and mean state evolution.

4.3. Evolution of EAWM over the last 2.8 Myr

Surface and subsurface temperature records from the same core provide a novel approach for evaluating low–high latitude connections, with SST more influenced by atmospheric forcing but subsurface temperature more influenced by ocean circulation forcing. Based on these differences, we expand on early suggestions to use upper water temperature vertical gradient in the northern SCS as a proxy for EAWM from the marine environments (Li et al., 2013; Steinke et al., 2011). Stronger EAWM could significantly stir upper water mixing and deepen the mixed layer; and this process results in significant SST cooling but less significant cooling for subsurface temperature, generating a smaller upper water thermal gradient (Fig. 2). Thus, vertical temperature difference (ΔTvertical) between USST - SST and TEXH - subsurface temperatures from the same sample set in our ODP Site 1147/48 is used as a proxy record of the EAWM variability during the last 2.8 Myr.

ΔTvertical was smaller during glacials (Fig. 4), as intensified winter monsoon wind could increase upper water mixing and hence resulted in smaller vertical thermal gradient; it was larger during interglacials, as weaker winter monsoon reduced upper water mixing leading to significant stratification and larger vertical thermal gradient. This glacial-interglacial pattern is consistent with the EAWM record reconstructed using QMGS from the Chinese Loess Plateau (Ding et al., 1995; Hao et al., 2012; Sun et al., 2006). Although resolution of ΔTvertical from the northern SCS is significantly lower than that of QMGS stack from the Chinese Loess Plateau, both records indicated that EAWM was stronger during glacial and weaker during interglacials (Fig. 4). For long term trend, EAWM was weaker from 2.7 Ma to 2.2 Ma, and stronger during 2.2–0.9 Ma (Fig. 4). This change coincided with the intensification of the Walker Circulation and Hadley Circulation (Etourneau et al., 2010), which favors stronger EAWM. However, in addition to EAWM intensity, the variation of thermocline depth in the SCS might also have affected ΔTvertical. For example, our ΔTvertical increased between 0.9 Ma and 0.7 Ma, coinciding with the shoaling of thermocline in the northern SCS (Jian et al., 2000; Zheng et al., 2005). This was further supported by the gradual contraction of western Pacific warm pool (WPWP) during this interval (Russon et al., 2010). During the last 0.9 Myr, ΔTvertical displays larger glacial-interglacial oscillations suggesting stronger EAWM variability, consistent with that recorded by the QMGS (Sun et al., 2006) and the phenomenon of larger NHIS variability (Lisiecki and Raymo, 2005).

In addition to glacial-interglacial cyclicity discussed above, the combined Chinese Loess Plateau and SCS records reveal a long term EAWM evolution cycle, with periodicity centered on 400 kyr, during 2.8–1.2 Ma (Fig. 8). In the following, we focus on mechanisms controlling the evolution of this 400 kyr in EAWM records. It has been proposed that EAWM evolution was controlled by NHIS through the Siberian High since the significant growth of NHIS (ca. 2.8 Ma), supported by the co-occurrence of glacial cyclicity, i.e. 41 kyr and 100 kyr, in both EAWM (Ding et al., 1995; Sun et al., 2006) and the NHIS record as indicated by δ18O stack (Lisiecki and Raymo, 2005). But there was no obvious 400 kyr cycle in the δ18O stack (Fig. 5a); thus the 400 kyr cycle in the EAWM records from the SCS and the Chinese Loess Plateau could not be easily explained by NHIS changes. Previously, the 400 kyr cycle in the EAWM record was attributed to the asymmetric response to insolation forcing based on the hypothesis that winter monsoon was more sensitive to colder intervals of the eccentricity modulated precession cycle (Sun et al., 2006). However, this could not explain the disappearance of 400 kyr cycle in the EAWM records over the last 0.9 Myr. Here, we propose a new mechanism for both the appearance of the 400 kyr cycle from 2.8 Ma to 1.2 Ma and for its absence during the middle-late Pleistocene (0.9–0 Ma) in EAWM records, by interactions of remote forcing between super ENSO state and the NHIS.

4.4. Super ENSO and NHIS modulated evolution of EAWM

The 400 kyr cycle has been observed in many paleo-climate records from the low latitude regions (Herbert et al., 2010; Li et al., 2011; Rickaby et al., 2007; Tiedemann et al., 1994), and it was caused by the annual maximum (and minimum) daily equatorial insolation which was modulated by eccentricity and characterized by pronounced 400 kyr and 100 kyr cycles (Ashkenazy and
400 kyr cycle in the ENSO records were most likely derived from the equatorial insolation forcing which is modulated by long eccentricity (Ashkenazy and Gildor, 2008).

For comparison, both EAWM and Pacific super ENSO state records displayed significant 400 kyr cycles from 2.8 Ma to 1.2 Ma, but no 400 kyr cycle was observed in the NHS accordingly (Fig. 9), with stronger EAWM and cold phase of super ENSO state occurring in low eccentricity state (Fig. 9), and vice versa. However, during the last 0.9 Myr, the 400 kyr cycle disappeared in EAWM records but was still significant in super ENSO state records (Fig. 9). These patterns suggest that the 400 kyr cycle originated from the tropics, and ENSO and NHS interactions likely played important roles in both the generation and absence of the 400 kyr cycle in EAWM records. Modern observation and model simulation reveal that EAWM intensity was reduced during warm phase of ENSO through generating lower-tropospheric anticyclonic anomalies over the Philippine Sea (Wang et al., 2000, 2010). Co-occurrence of reduced (intensified) EAWM and warm (cold) super ENSO state had also been observed on geological time scales and evidences are as follows: (1) On glacial-interglacial time scale during the Pleistocene, zonal SST gradient between western and eastern equatorial Pacific was larger during glacial stages, analogous to the La Niña state of the modern Pacific (Lea et al., 2000; Sadekov et al., 2013); and the EAWM was stronger as indicated by evidence from the Chinese Loess (An, 2000; Porter and An, 1995), and from the SCS (Huang et al., 2011; Steinke et al., 2011). (2) On tectonic time scale during the Pliocene epoch (5–3 Ma), WPWP was larger and tropical Pacific was characterized by super El Niño state as indicated by smaller $\Delta T_{\text{TW-E}}$ (Wara et al., 2005), while QMGS stack that derived from the Chinese Loess indicated weaker EAWM in the Pliocene (Sun et al., 2006).

Basing on the above evidence, we propose that modulation by ENSO was the most important factor for generating the 400 kyr cycle in the ENSO records.
eccentricity cycle in the EAWM record between 2.8 and 1.2 Ma. During high eccentricity state (Fig. 10a), earth received larger total insolation resulting in warmer climate state as indicated by higher SSTs in both eastern and western tropical Pacific (Fig. 7). The tropical Pacific was in a warm phase of super ENSO state (Fig. 9c), which favored eastward location of WPWP and the related eastward movement of Walker Circulation lower-tropospheric center (Fig. 10a). Under this condition, the western branch of Walker Circulation generated anticyclonic center over western Philippine Sea and hence reduced the EAWM intensity (Fig. 10a). While during low eccentricity state (Fig. 10b), the tropical Pacific was in cold super ENSO state (Fig. 9c and Fig. 10b), westward location of WPWP generated Walker Circulation center over the western Philippine Sea, and this cyclonic atmospheric circulation favored intensification of EAWM.

Since northern high-latitude climate forcing on EAWM variability is also well known (Ding et al., 1995; Sun et al., 2006), then EAWM evolution during the last 2.8 Myr must have been the result of interactions between NHIS and Pacific super ENSO changes. NHIS increased gradually from 2.8 Ma to 1.2 Ma, but it’s volume was relatively small and thus the Siberian High center should be located northward with weaker intensity; hence the Pacific ENSO influence on the EAWM region was stronger during this period (Fig. 10c). The combinations of weak high latitude forcing and strong low latitude ocean influence caused the occurrence of both the 41 kyr (from NHIS) and 400 kyr (from Pacific super ENSO) cycles in EAWM record (Fig. 10c). During the mid-Pleistocene Transition (MPT, 1.2—0.6 Ma), earth’s climate experienced significant internal change without any significant change of orbital forcing (Laskar et al., 1993). The NHIS grew extensively through the MPT, ca. 50 m sea-level equivalent (Clark et al., 2006); thus further expansion of NHIS forced the southward migration of the Siberian High center and hence increased high latitude forcing on EAWM (Fig. 10d). Meanwhile, the colder state of super ENSO reduced the influence of low latitude ocean on EAWM mean state during the middle-late Pleistocene (Fig. 10d). This low-high latitude interaction resulted in EAWM variations characterized by the dominance of the 100 kyr cycle and the absence of the 400 kyr cycle (Fig. 10d), although the super ENSO state was still paced by 400 kyr cycle.

As a part of the global monsoon system, possible interactions between the EAWM system and other tropical climate processes must be considered, e.g. intertropical convergence zone (ITCZ), the Australian monsoon, and the Indian monsoon, on orbital/geological time scales. During the modern boreal winter, ITCZ migrates southward and lies over northern Australia (Schneider et al., 2014); Meanwhile, the Australian summer monsoon prevailing in the north Australia and the Arafura Sea. For the Quaternary, both model results and record results suggest that the evolution of the Australian summer monsoon was affected by the EAWM through trans-equatorial outflow from the East Asian Siberian High in winter (An, 2000; Magee et al., 2004; Miller et al., 2005; Wyrwoll et al., 2007). In addition, it had also been reported that during high obliquity state in the Quaternary, the pressure gradient between intensified Siberian High (stronger EAWM) and Australian low enhanced cross-equatorial flow and reinforced the southward shift of the ITCZ rain belt to the southernmost position in boreal winter (Liu et al., 2015). Thus, EAWM (Siberian High) affected/ modulated the evolution of ITCZ as well as the Australian summer.

![Schematic illustration of interactions between ENSO and IS, and its effect on EAWM.](image-url)
monsoon (Liu et al., 2015; Shiau et al., 2012; Wang et al., 2003), but not vice versa. However, reconstructions for the evolution of Indian winter monsoon on orbital cycles have not been reported so far. Modern climate observations show that the Indian winter monsoon wind intensity was much weak than that of the EAWM, and no direct connection existed between these two monsoon systems due to the blocking of cold Siberian air by the Tibetan Plateau (Wang et al., 2003). By analogue, it is reasonable to postulate that Indian winter monsoon influence on the EAWM was negligible during the Quaternary.

Our proposed mechanism has important implications for both understanding past climate changes in monsoon dominated regions and globally, as well as for predicting the evolution of EAWM in the future under global warming conditions. For example, evolution of the East Asian summer monsoon (EASM) and the EAWM displayed negative correlation during glacial-interglacial cycles over the last 2.8 Myr, with stronger winter monsoons shifted toward ice maxima and strong summer monsoons shifted toward ice minima (Clemens et al., 2008). Similar to that of EAWM, a strong 400 kyr cycle was also observed in the EASM record during the 2.8–1.2 Ma (Sun et al., 2006), which might be the result from modulation by Pacific super ENSO because EASM were reported to be affected by Pacific ENSO state (Wang et al., 2003). For further understanding of the teleconnections between Pacific ENSO and East Asian monsoons on millennial and glacial time scales requires high resolution paleo-records from monsoon sensitive land and ocean regions; in addition, further paleo-climate model simulations are necessary to test our postulation discussed above. In terms of our postulation on long eccentricity cycle, if anthropogenic global warming continues in the future, EAWM will be more influenced by tropical ENSO as northern hemisphere high latitude ice volume continues to decrease.

5. Conclusions

Surface and subsurface water temperature records were reconstructed from the northern SCS using $^{13}C_{PDB}$ and TEX_{SH} indices over the past 2.8 Myr. The upper water vertical thermal gradient provides insights into the evolution of EAWM in subtropical regions. Main conclusions are as following:

1. Both surface and subsurface temperature records from ODP Site 1147/48 show similar glacial-interglacial oscillations with that of global benthic foraminiferal $^{18}O$ record, displaying significant 41 kyr cycle between 2.8 and 0.5 Ma and 100 kyr between 0.7 and 0.1 Ma. In addition, a 400 kyr cycle is observed in SST but not in subsurface temperature and Northern Hemisphere ice sheets records ($^{18}O$), suggesting the evolution of subsurface water temperature was more tightly linked with high latitude climate.

2. Vertical temperature difference ($\Delta T_{vertical}$) from the northern SCS was smaller during glacials suggesting stronger EAWM, and was larger during interglacials suggesting weaker EAWM. The combined Chinese Loess Plateau and SCS records reveal a significant 400 kyr cycle in EAWM evolution during 2.8–1.2 Ma, with weak (strong) EAWM intensity during high (low) eccentricity state.

3. By combining with Pacific super El Niño–Southern Oscillation (ENSO) state which has a 400 kyr cycle throughout the last 2.8 Myr with warm (cold) phase during high (low) eccentricity state, we propose that the evolution of EAWM was strongly modulated by super ENSO mean state through remote forcing to generate the 400 kyr ENSO cycle between 2.8 Ma and 1.2 Ma; while during the last 0.9 Myr, a further expansion of NHIS increased high latitude forcing on EAWM resulting in the dominance of 100 kyr cycle but the absence of the 400 kyr cycle.

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Contributions

M.Z. and J.T designed the study. D.L carried out measurement of biomarkers and calculation of TEX_{SH} and U_{37}C, and synthesized previously published data. D.L and M.Z wrote the paper, and all co-authors provided intellectual input for data interpretation.

References