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# The East Asian winter monsoon over the last 15,000 years: its links to high-latitudes and tropical climate systems and complex correlation to the summer monsoon

Luo Wang[a,*], Jingjing Li[b], Houyuan Lu[a], Zhaoyan Gu[a], Patrick Rioual[a], Qingzhen Hao[a], Anson W. Mackay[c], Wenying Jiang[a], Binggui Cai[a], Bing Xu[a], Jingtai Han[a], Guoqiang Chu[a]

[a] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] School of Geosciences and Resources, China University of Geosciences, Beijing 100083, China
[c] Environmental Change Research Centre, Department of Geography, University College London, London WC1E 6BT, UK

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ABSTRACT

The East Asian winter monsoon (EAWM) not only plays an important role within the Asian climate system, but also carries cold air from the high northern latitudes across the Equator to the Southern Hemisphere, acting as a link between the polar and tropical climate systems. However, past changes of the EAWM have not been clearly established so far due to the lack of suitable proxy records. Here, we at first establish an index of the EAWM by comparing the results of a sediment trap experiment and 100-year sedimentary record from Huguang Maar Lake (HML) with modern records of the EAWM, Siberian High (SH) and Arctic Oscillation (AO). Secondly, we present a continuous record of the strength of the EAWM for the past 14,500 years based on sedimentary diatom assemblages in HML. The record is derived from fluctuations in the relative abundance of two planktonic diatom species. The link with the EAWM intensity is through high wind speeds inducing turbulent mixing, which stimulates the productivity of the meroplanktonic species *Aulacoseira granulata*. The diatom record of the past 14,500 years shows that the EAWM shifted from strong to weak from the early to late Holocene. This linked to both changes in winter temperature at high-latitudes and in El Niño conditions in the tropics. Our record shows that the EAWM and East Asian summer monsoon (EASM) as recorded in stalagmites, were in-phase instead of anti-correlated on orbital time scales during the Holocene. On a millennial time scales, the EAWM was anti-phase with the EASM during the Last Glacial–Holocene transition. However, during the early–middle Holocene the relationship between the EAWM and EASM shows spatial variations. In northern China, the records show significant anti-phase, but in southern China the anti-phase was not observed. During the late Holocene, we did not find any clear relationship between the EAWM and EASM. We also explored the link between the EAWM and the Australian summer monsoon (ASM). Anti-phase of the ASM with summer insolation in the Southern Hemisphere is an enigmatic exception that cannot be explained by the classic theory of insolation. During early Holocene the EAWM was in-phase with the Australian summer monsoon (ASM), which provides the first direct evidence to support the hypothesis that the intensity of the EAWM affected, at least in part, the strength of the ASM.



## 1. Introduction

The East Asian winter monsoon (EAWM) is one of the most active components in the global climate system. It generally refers to the atmospheric flow over Asia associated with movement of cold air coming from the Siberian High (SH) (Fig. 1) (Chen et al., 1991; Ding, 1994; Huang et al., 2003, 2007; Chan and Li, 2004; Chang et al., 2006). The SH, also called Siberian anticyclone, is a semi-permanent system of high atmospheric pressure centered in northeastern Siberia during the colder half of the year, when the air temperature near the center of the high-pressure cell is often lower than −40 °C. The SH affects the weather patterns in the higher latitudes of the Northern Hemisphere, it is responsible both for severe cold and dry conditions in winter across Siberia and most of China (Oliver, 2005). The variability of the EAWM depends largely on the behavior of the SH (Gong and Ho, 2002) and Arctic

* Corresponding author. Tel.: +86 10 82998261; fax: +86 10 62032495.
*E-mail address:* wangluo@mail.iggcas.ac.cn (L. Wang).

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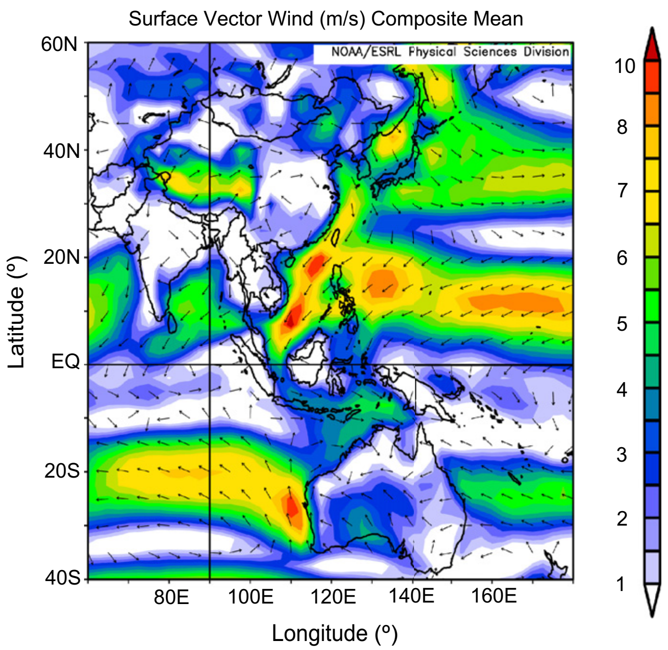


**Fig. 1.** The characteristics of surface winds of January (based on the NCEP/NCAR reanalysis data) (Kalnay et al., 1996). To best illustrate the path of surface winds we chose data from 1960 to 1985 AD, as this interval corresponds with strong winter monsoon. HML means the location of Huguang Maar Lake.

Oscillation (AO) (Gong et al., 2001). AO was introduced as an annular mode of atmospheric circulation by Thompson and Wallace (1998). Fluctuations in the AO create a seesaw pattern in which atmospheric pressure and mass in northern polar and mid-latitudes alternate between positive and negative phase (Wallace, 2000). When the AO is in a negative phase and the SH is strong, the temperature is cold at high northern latitudes, resulting in a strong EAWM (D'Arrigo et al., 2005). In addition, the EAWM have been linked to the El Niño/Southern Oscillation (ENSO) (Li, 1990; Li and Mu, 2000; Wang et al., 2000; Xu and Chan, 2001; Wang et al., 2008a). A weak EAWM usually occurs during an El Niño year, but the reverse occurs during a La Niña year (Li, 1989).

When the EAWM shifts southward, it not only covers northern China and Japan (Chen et al., 2005; Wang et al., 2009), but its southern branch also forms northeasterlies which penetrate through the South China Sea and across the tropics into the Southern Hemisphere (Fig. 1) (Suppiah and Wu, 1998; Gong and Ho, 2002; Jhun and Lee, 2004; Miller et al., 2005). The EAWM therefore, not only influences the East Asian summer monsoon (EASM), but also affects convection over the maritime continent and the Australian summer monsoon (ASM) (Chen et al., 1991; Suppiah and Wu, 1998). It is necessary therefore for us to improve our knowledge of the EAWM in order to understand climate dynamics in this vast region.

So far, most of our knowledge on past changes of the EAWM comes from loess records from the Chinese Loess Plateau. The grain size of loess have been used as an indicator to reconstruct the changes of the EAWM on orbital and millennial time scales (An et al., 1991a; Porter and An, 1995; Xiao et al., 1995; An and Porter, 1997; Liu and Ding, 1998; Liu et al., 1999; Ding et al., 2002; Lu et al., 2004; Porter and Zhou, 2006). When the EAWM is strong, it carries coarse dust to the Chinese Loess Plateau resulting in the increase of the grain size in loess records (An et al., 1991a). On orbital time scales, changes in the EAWM have been linked to changes in ice volume in the Northern Hemisphere (Ding et al., 1995; Liu and Ding, 1998; Porter, 2001), which is primarily controlled by the Northern Hemisphere summer insolation at 65°N (Hays et al., 1976; Imbrie et al., 1984; Ruddiman et al., 1989; Shackleton et al., 1990). The view is that the Northern Hemisphere ice sheets indirectly influenced the EAWM by exerting an important control on the intensity of the SH. During glacial, the large ice sheets resulted in cold surface conditions in Siberia and strong SH that lead to strong EAWM. In contrast, during interglacial small ice sheets resulted in weak SH and weak EAWM. During the Holocene, the grain size of many Chinese loess records (Yang and Ding, 2008) and the high-resolution record of titanium concentration from the Huguang Maar Lake (HML) (Yancheva et al., 2007) indicate that the EAWM strengthened through time from low intensity during the warm early Holocene to high intensity during the cool late Holocene. However, it has been shown that Northern Hemisphere ice sheets in land were larger during the early–middle Holocene than during the late Holocene (Dyke and Prest, 1987; Kutzbach et al., 1998). The winter insolation in Northern Hemisphere is lower during early Holocene than during late Holocene (Berger and Loutre, 1991). Such change in the size of ice sheets and the insolation should have caused a weakening of the EAWM from the early to late Holocene. This contradiction needs to be explored.

Recent studies indicated that the grain size of loess not only was controlled by the EAWM, but was also influenced by the EASM, which controls the advance or retreat of the boundaries between the areas of desert and loess (Yang and Ding, 2008). Therefore, it is still open to debate whether the grain size in loess records is a robust index of the EAWM strength. The reliability of the titanium record from the HML as an indicator of the EAWM (Yancheva et al., 2007) has also been questioned. This is because titanium may not be carried by winter winds from the Chinese Loess Plateau, but may be derived from erosion by rainfall running off the HML catchments or water level changes (Zhou et al., 2007, 2009). Another index for reconstructing changes in the EAWM has been derived from the west–east/north–south gradients in sea surface temperatures established for the northern part of the South China Sea (Tian et al., 2010; Huang et al., 2011). However, these marine sediment records compared to lake records have a rather low temporal resolution over the Holocene.

There is therefore a clear need to develop a new, high-resolution, independent proxy record of the EAWM. Wang et al. (2008b) used high-resolution diatom assemblages as a proxy indicator of the EAWM from HML in subtropical China during the Lateglacial–early Holocene transition. Here we expand on that study, by reconstructing the EAWM from the late Last Glacial (14.5 ka BP) through the complete Holocene sequence up to the present using the same sediment core. We provide new, additional evidence linking diatom assemblage change to winter monsoon through extended sediment trap studies, and the comparison of diatom assemblages with indices of the SH and AO over the last c. 110 years. We discuss the correlation between the EAWM and EASM on orbital and millennial time scales, and possible linkages to the EAWM and Australian summer monsoon (ASM).

## 2. Geographical setting

HML (21°9′N, 110°17′E, Fig. 2) is located in Guangdong Province, near the coast of South China Sea. HML is a crater lake, with a diameter of ~1.7 km and a maximum depth of ~20 m. This lake is influenced by both the Asian summer and winter monsoons (Fig. 2). During winter, the strong EAWM covers northern China and bifurcates south with one branch flowing along the coast of East Asia (Lau and Li, 1984; Ding, 1994; Chen et al., 2000, 2005; Wang et al., 2009). Therefore, the EAWM winds blowing over HML come from the northeast (Fig. 1). These are responsible for the complete mixing of the HML water column. During summer, by contrast, the lake strongly stratifies due to weak winds and high temperatures (Wang et al., 2008b).