Quaternary Science Reviews 149 (2016) 102–108

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Cold surges and dust events: Establishing the link between the East Asian Winter Monsoon and the Chinese loess record

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ARTICLE INFO

Article history:
Received 11 November 2015
Received in revised form
8 April 2016
Accepted 15 April 2016
Available online 31 July 2016

Keywords:
Loess
Winter Monsoon
East Asia

ABSTRACT

The Chinese loess/palaeosol succession is one of the most comprehensive and intensively studied archives of Neogene and Quaternary global palaeoclimate events. Its stratigraphic details are widely recognised to indicate close links to the history and function of the East Asian Winter Monsoon (EAWM) – one of the most active components of the Earth's climate system. But the formal meteorological links between the EAWM and dust emission, both in the present day and in the past, have not been established and with it, the veracity of the loess record as an indicator of the EAWM questioned. Here we show that present day major dust events over northern China, while largely occurring during spring, are nevertheless 'conditioned' by the strength of the preceding EAWM. We also demonstrate, for the first time, a close link between the occurrence of dust events and the strength of the EAWM. From these findings, linked to global-scale climate model simulations, we conclude that the Chinese loess succession provides a convincing proxy record of the strength of the East Asian Winter Monsoon.

1. Introduction

The stratigraphy of the Chinese Loess Plateau, comprising interbedded loess and palaeosol sequences, provides an iconic Quaternary terrestrial record of East Asian glacial and interglacial events. The 'Red Clay' sequences extend the record into the early Neogene, and through this captures both East Asian 'inland aridification' and the on-set of the East Asian monsoon regime. (Ding et al., 1992; Liu and Ding, 1998; Guo et al., 2002; Stevens et al., 2007; An et al., 2014). The Quaternary component of the succession played a fundamental role in establishing the correlation between the terrestrial and marine glacial-interglacial records, stressing the loess record's global significance (Heller and Liu, 1982; Kukla, 1987; Ding et al., 2002; Williams, 2014) This correlation carried the implication that the East Asian glacial-interglacial scale climate shifts, were captured through dust entrainment, transport, deposition and post-depositional sediment 'modification', which in turn meant that the loess record provides a register of the function and intensity of the East Asian monsoon (EAM) regime (An et al., 1990, 2014; Liu and Ding, 1998).

Various loess related proxies have been used to reconstruct monsoon events. The record of East Asian Summer Monsoon (EASM) variability has been related to the weathering imprint of inter-bedded palaeosols with, traditionally, some emphasis on magnetic susceptibility (e.g., Heller and Liu, 1984; An et al., 2014). In the reconstruction of the East Asian Winter Monsoon (EAWM) variations, strong claims have been drawn from changes in the rates of deposition – mass accumulation rates (MAR) - and loess grain-size changes, not always without difficulties (Stevens et al., 2007). From these studies has emerged: (i) the general claim of a strengthening of the EAWM during glacial stages with a significant downturn of EAWM activity during interglacial stages (e.g. Stevens et al., 2007; Hao et al., 2012; An et al., 2014); and (ii) the recognition of more short term stadial-interstadial to millennial scale events (Porter and An, 1995; Sun et al., 2010, 2011; An et al., 2014).

Linked to an understanding of the East Asian component of the

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http://dx.doi.org/10.1016/j.quascirev.2016.04.015
0277-3791/

Asian monsoon winter regime at a range of time scales, are far-reaching implications, including the possibility of deciphering possible Atlantic–EAWM and EAWM–Indonesian–Australian Summer Monsoon teleconnections (Sun et al., 2011; Wyrwoll et al., 2007; Wang et al., 2012; Denniston et al., 2013). The recognition of millennial scale stronger EAWM events further emphasises the importance of the loess record in pointing to the global imprint of such events (Porter and An, 1995; Sun et al., 2011; Denniston et al., 2013).

These palaeoclimate interpretations of the significance of inferred winter loess depositional rates and grain size changes have been recently cast into doubt by claims that the record of dust events in the Chinese loess succession does not relate to a stronger EAWM (Roe, 2009; Lu et al., 2011). The claims have now entered the more general literature (Williams, 2014:153) and challenge a vast research effort with far-reaching implications for our understanding of global scale climate teleconnections and drivers.

Roe's (2009) claims are based on the fact that present-day dust events occur in spring and hence do not relate to or indicate winter synoptic states. Roe (op. cit.) recognises that such dust events are driven by strong winds associated with cyclogenesis and the passage of strong cold fronts, and points to the fact that such events occur as a result of the breakdown of the Siberian High – the ultimate driver of the EAWM.

The details of proposed EAWM changes, whether in strength and/or frequency, have generally not been firmly grounded in a framework of the controlling climate drivers. With associated discussions bringing with them an element of circularity – high mass accumulation rates (MARs) and 'coarse' grain-size indicate a stronger EAWM, and from a stronger EAWM, high MARs and 'coarse' grain-sizes can be expected. Our objective here is to break this nexus and specifically determine the relationship between dust events–loess deposition and the strength of the EAWM. We attempt this by focusing on the controlling climatology of dust events and employ Ocean Atmosphere Global Climate Model simulation results for selected periods over the last 21,000 years to strengthen our claims.

2. Cold surges in the climatology of the East Asian Winter Monsoon

The EAWM dominates the climate of East Asia during the winter months (e.g., Chang et al., 2006) and is closely associated with the development of a cold core high pressure system over the Siberian-Mongolian region (Fig. 1). The strength of the EAWM is defined through the associated surface pressure and/or a consideration of the details of its dynamic controls (Jhun and Lee, 2004; Li and Yang, 2010). During the EAWM, the Siberian High with its central pressure reaching in excess of 1035 hPa, dominates much of the Eurasian continent; individual cases of central pressure as high as 1085 hPa have been reported. More strong northwesterly flows occur at its eastern margins, where the flow separates into one branch directed eastward into the subtropical western Pacific, and then tending southward in the direction of the South China Sea. At 500 hPa, a trough (the East Asian Trough) is evident, aligned with the longitudes of Japan. At 200 hPa, the Polar East Asian Jet is prominent, with its maximum located just southeast of Japan. The Polar Jet is associated with strong baroclinic instability, large vertical wind shear and cold air advection.

The cold air 'excursions', also described as 'cold surges', are channeled by the trough southwards and are a characteristic feature of the EAWM (Lau and Chang, 1987) that impact strongly on the winter climate of eastern China. Their path is in part related to relief controls of the Tibetan Plateau, with their effect extending to the tropics, where they can lead to the flare-up of convective activity over the Maritime Continent (Chan and Li, 2004). The recognition of cold-surges as a meteorological feature extends back to the early part of the last century (Li, 1954; Lu, 1954). They were then termed 'cold waves' and were recognised as being associated with 'sandstorms' (Lu, 1954). Lu (op.cit.) described an event in March 1936, which could be traced over much of east China extending into the south and associated with a regionally extensive

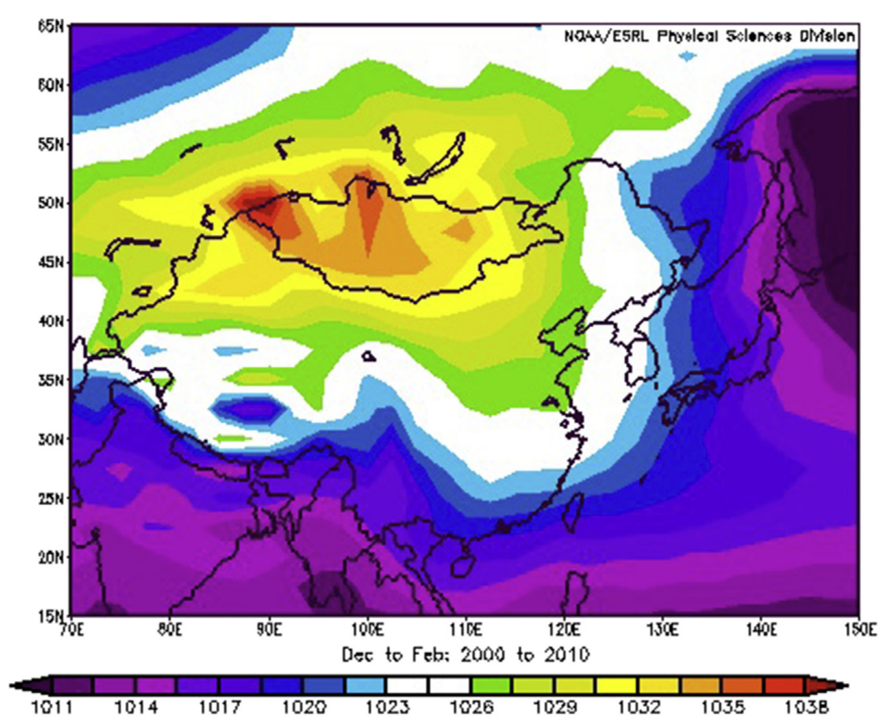

Fig. 1. December/January/February sealevel pressure (mb) – 2000–2010 (NCEP/NCAR Reanalysis).

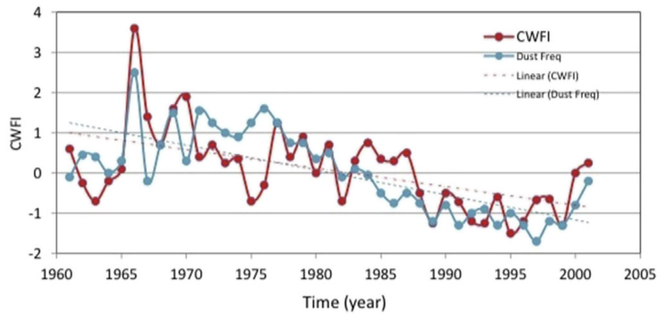

Fig. 2. Normalized winter Cold Wave Frequency Index (CWFI; red solid line; red marks; unitless), normalized spring dust event frequencies (blue solid line; blue marks; unitless), and their linear trends (dash lines) for the period 1961–2001. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sandstorm.

It is now recognised that the frequency of cold-surges can act as a surrogate for the strength of the EAWM (i.e. surface pressure) (Zhang et al., 1997; Ding and Sikka, 2006). For the period 1979–1995, Zhang et al. (1997) found an average annual occurrence of 13 cold surges per year based on the NCEP/NCA reanalysis data. Using different criteria, Chen et al. (2004) proposed that about 17 events occur every winter. Cold surges can last from 5 to 14 days (Zhang et al., 1997), hence forming a significant component of the winter climate of the southern East Asia – South China Sea region. But cold surges do not necessarily constitute dust depositional events, as emphasised by Roe (2009). In the present climate, the frequency of large-scale Asian dust events peaks between March and May (Shao and Dong, 2006), with more than 85% of the annual dust storms occurring during spring (Zhu et al., 2008). The annual number of dust events originating from the Gobi Desert ranges between 20 and 35 (Sun et al., 2001), and given their mainly spring occurrence, they would appear to be a poor indicator of the strength of the EAWM.

3. Methods

To establish the relationship between cold air outbreaks in winter (i.e. the strength of the EAWM), and dust activities in spring, we analysed cold surge events recorded at stations maintained by the China Meteorological Administration in North China (north of 34° N) over the 41-year time period between 1961 and 2001. Initially, the data-sets employed in this study are from the daily mean surface temperature recorded at 833 stations across China by the China Meteorological Administration. In order to focus on northern China, this study examines only the stations that are north of 34° N. Then, all records of station records north of 34° N were screened for missing data and stations with too many missing values were removed. A station year is considered ‘missing’ if more than 1% of the days are missing. After screening, a total of 280 stations with ‘non-missing’ years during the study period could be retained. Here, a cold surge event at a single station is defined if the event-temperature drop ΔT exceeds 10 °C and the event minimum temperature T_{min} is lower than its 10-day climate mean by −5 °C. By averaging and then normalising the time series for the 280 stations during winter, a cold wave frequency index (CWFI) was derived. Wei and Lin (2009) provide further details of the calculations involved and Wang and Ding (2006) and Ma et al. (2008) provide examples of the applications of the criteria derived.

Corresponding dust event frequencies were obtained from synoptic data from 162 weather stations in Northern China (data available from the China Meteorological Administration). For these stations, days with dust events (also generally described as “dust weather”), including dust storms, blowing dust and dust in suspension, were registered. For an individual station, dust frequency is defined as the total number of days between March and May in which a dust event is observed. Zhou et al. (2006) provide a detailed introduction to these data-sets.

4. Results

The correspondence between the dust event frequency and CWFI series (Fig. 2) yields a correlation coefficient of 0.73. The time series show a matching decreasing trend with time, and on detrending both, the positive correlation of 0.4 is retained. These data clearly suggest that a high winter cold surge frequency in northern China is accompanied by a high dust event frequency in the following spring.

In order to provide more details on the likely relationship between dust and cold-surge events, ‘strong’ (>0.7) and ‘weak’ (<−0.7) CWFI years were selected and composite analyses of the corresponding dust events in the following spring were carried out. The composite analyses confirm a significant correspondence between the winter cold surges and spring dust events. The results clearly show that the CWFI and dust frequency are positively correlated, making it evident that when the winter cold surge frequency in northern China is high, then the following spring dust event frequency is also high (Fig. 3).

5. Discussion

The circulation controls of matching high (low) dust/strong (weak) CWFI events are highlighted by the difference in the spring

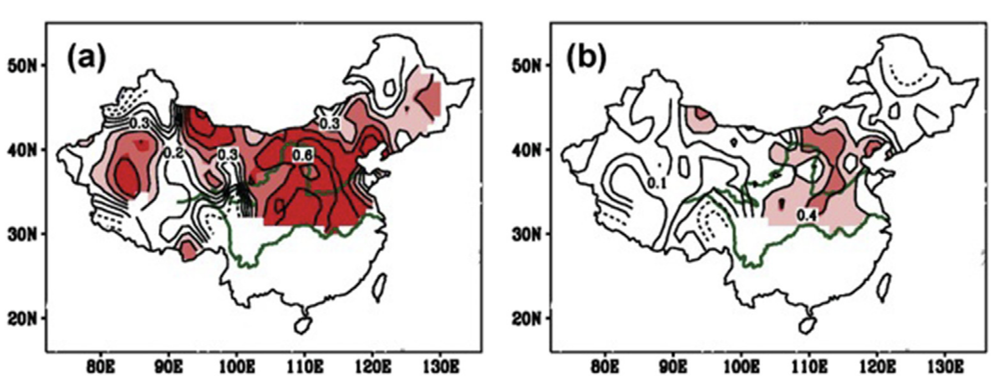

Fig. 3. Correlation between CWFI and spring dust event frequencies – shaded area significant at 95%, 99%, and 99.9% confidence level, respectively: (a) raw data, (b) detrended data.

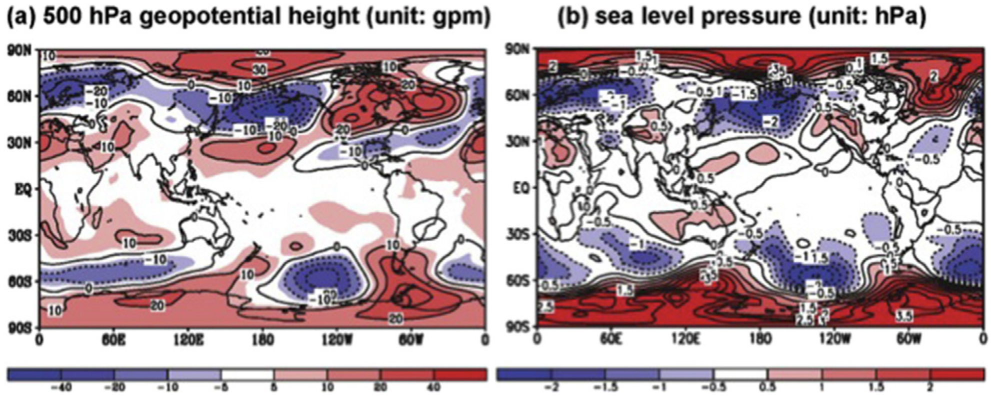

Fig. 4. Differences between strong (high dust frequency) and weak (low dust frequency) CWFI years: (a) spring 500 hPa geopotential height (unit: gpm), (b) spring sea level pressure (unit: hPa).

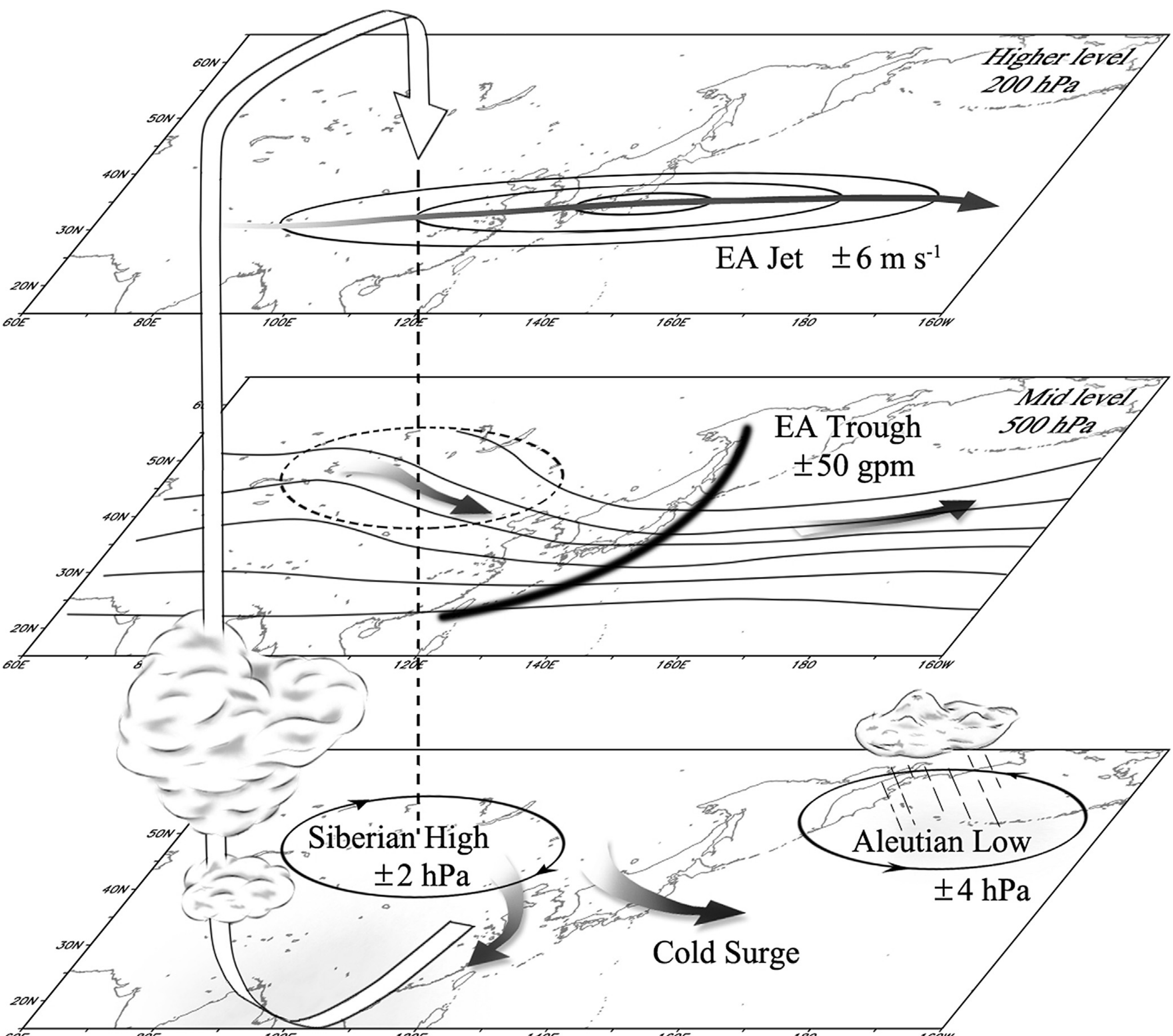

Fig. 5. Conceptual representation of the synoptic expression of strong EAWM years promoting cold surges and the incidence of dust events over northern China.

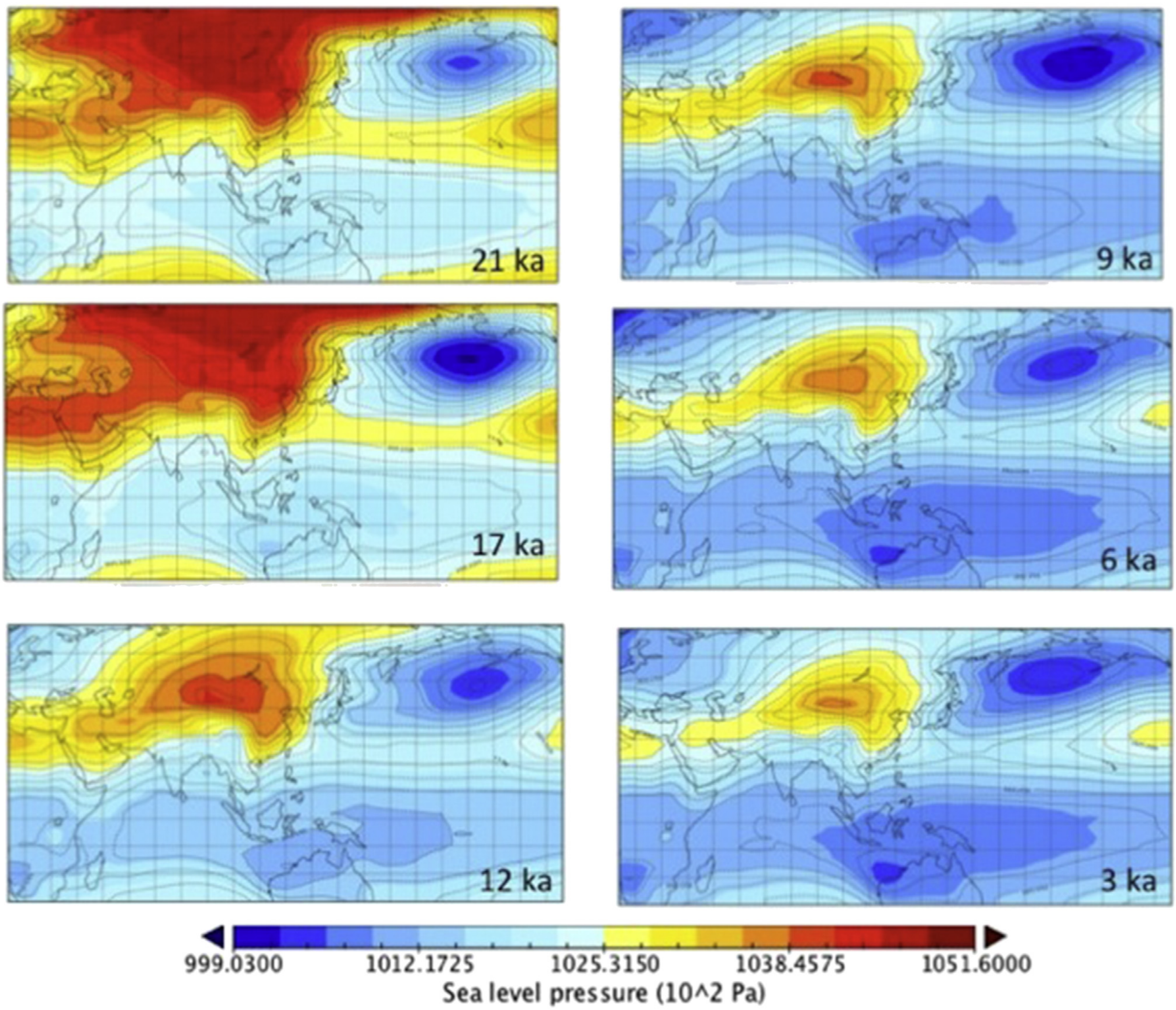

Fig. 6. Winter (DJF) model sea level pressure for selected time periods in the last 21,000 years.

500 hPa geopotential height and spring sea level pressure between 'strong' and 'weak' CWFI years (Fig. 4). In comparing the two composites, the deepening of the Aleutian Low is prominent and in strong CWFI years, the East Asian Trough is on average, 20 gpm lower, with surface pressure differing by 2 hPa. During a strong CWFI year (high dust frequency year), the Siberian High is relatively strong; the Aleutian Low is relatively deep with its western part having a stronger northerly wind component; the Polar High is strong; the European Shallow Trough is relatively deep; the East Asian Trough is deep and the Ural Ridge is strong. A conceptual overview of the three-dimensional structure of the EAWM during strong EAWM years is given in Fig. 5. The outlined circulation controls can be placed into the more general context of hemisphere-scale conditions (Gong et al., 2001; Wei and Lin, 2009; Park et al., 2011; Chang and Lu, 2012). Gong et al. (2006) established a correlation between the inter-annual variation of dust storm frequency over northern China and the Arctic Oscillation (AO). A negative phase of the AO is associated with a deeper East Asian Trough and a strong Siberian High with associated cold surges in northeast Asia (Gong et al., 2001; Wu and Wang, 2002) – i.e. a strong EAWM. This reconstruction emphasises that during strong EAWM years, the Siberian High has a relatively high surface pressure, with the Aleutian Low relatively deep and with its western part having a strong northerly wind component. The East Asian Trough is deeper with a strong Polar Jet evident in the upper troposphere. These configurations lead to stronger winter cold air outbreaks followed by dust events in the following spring.

The Siberian High forms in response to strong radiative cooling in the lower troposphere, confining it to the lower levels of the troposphere – below 500 hPa (Panagiotopoulos et al., 2005). Consequently, given these controls and the correspondingly shallow nature of the Siberian High, it is to be expected that it was significantly enhanced during glacial stages. To support our claim, we use results from a transient simulation of the last 21,000 years (TraCE-21K – Liu et al., 2009; He et al., 2013) with the coupled atmosphere–ocean Community Climate System Model Version 3 (CCSM3). Fig. 6 shows the simulated sea surface pressures over the East Asian region for selected time periods during the last 21,000 years. The model results indicate a strengthening of the Siberian High during glacial stages, showing progressive weakening of the Siberian High by 12 ka, with this trend continuing into the Holocene. From the model results and the present day relationship between the strength of the Siberian High, cold surges and dust events, the inference of an increase in the frequency of cold surge events during glacial stages follows.

Given the clear association of dust events and the strength of the Siberian High (i.e. the EAWM), it follows that glacial (interglacial) stages were characterised by high (low) loess mass accumulation rates (MAR), possibly associated with coarser (finer) loess grain-sizes (e.g. Kohfeld and Harrison, 2003; Stevens et al., 2007; Sun et al., 2011; Kang et al., 2013; An et al., 2014). In providing a more secure chronology, Kang et al. (2015) have been able to give more refinement to these claims. They demonstrate that despite significant variations, all sites considered by them show increased MARs during ~26–19 ka, with notable peaks in some stratigraphic successions during 23–19 ka. Generally lower MARs were recognised for the time period, 19–12 ka. These results show a general correspondence with the strength of the model reconstruction of the Siberian High (Fig. 6), with decreasing strength of the Siberian High corresponding to lower MARs. In this it should not be overlooked that land surface characteristics can be a control on dust entrainment and that this may be reflected in MARs. For instance, the distribution of frozen ground at the Last Glacial Maximum (Liu and Jiang, 2016) is likely to have had an impact on entrainment rates and hence the 'matching' MARs of some loess successions.

While our model results point to a strengthening of the Siberian High during glacial stages and hence a stronger EAWM, the degree to which this can be expected to be apparent in loess grain-size variations may not always be straightforward. It is generally recognised in the Chinese loess literature that grain-size characteristics are related to source controls, transport paths and wind strength (e.g., Pye, 1997; cited in An et al., 2014) But despite these complexities, a strong claim exists for a link between the grain-size characteristics of Chinese loess and the strength of the EAWM (summary in An et al., 2014: 54–57). The potential importance of such claims is highlighted by the recent findings of Sun et al. (2011). Using the Gulang and Jinguan loess successions, they argue that grain-size variations over the last ~60,000 years reflect changes in the strength of the EAWM and draw the conclusion that Atlantic meridional overturning imprints itself on the EAWM through changes in the westerly circulation that 'transmits' this signal from the North Atlantic to the EAWM region (Sun et al., 2011). These are very important inferences that stress the need for focused field and climate modeling work, specifically addressing the questions of the controls of loess grain-size. A need that is further emphasised by the recent Nie et al. (2015) claim of the link between Yellow River sediment sources and the development of the Chinese Loess Plateau.

6. Conclusions

Given that the strength of the EAWM is positively related to the occurrence of dust events, it follows that the details of the Chinese loess record serve as valid proxy indicators of the strength of the EAWM. In this claim, we use the term 'strength' of the EAWM in the strict sense, i.e., related to the frequency of cold surges, which is determined by the northern hemispheric circulation in northeast Asia, with the strength of the Siberian High, as measured by its central pressure, being a key driver. Accepting this inference and combining it with the recent advances in loess dating techniques, recognition of regional depositional patterns, 'switching' loess sources and climate modeling, brings with it the potential for a comprehensive reconstruction and understanding of the dynamic palaeoclimatology of the EAWM over long time scales and through this, 'capturing' wider global scale climate teleconnections and drivers.

Acknowledgements

This research was jointly supported by the CAS Strategic Priority Research Program (XDA05110200) and International S&T Cooperation Program of China (No. 2011DFG23450. KHW wishes to thank Wang Xulong for discussion, Lu Yanchou who prompted his interest in Chinese geology, Karen Wyrwoll for the usual assistance and Pat Behling for her help with the TRACE-21K data. F.H. was supported by the US NSF (AGS-1203430) and by the NOAA Climate and Global Change Postdoctoral Fellowship program, administered by the University Corporation for Atmospheric Research. This research used resources of the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725. This study is funded by the German Research Foundation (DFG) through the CRC 806 (Our way to Europe). We thank Martin Williams and an anonymous referee for their comments.

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