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

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39 **Abstract**

40 The Chinese loess/palaeosol succession is one of the most comprehensive and intensively studied
41 archives of Neogene and Quaternary global palaeoclimate events. Its stratigraphic details are widely
42 recognised to indicate close links to the history and function of the East Asian Winter Monsoon (EAWM)
43 – one of the most active components of the Earth’s climate system. But the formal meteorological links
44 between the EAWM and dust emission, both in the present day and in the past, have not been established
45 and with it, the veracity of the loess record as an indicator of the EAWM questioned. Here we show that
46 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 inter-bedded 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, 1984; 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., 1991; Liu and Ding, 1998; An et al., 2014) .

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, 1982; An et al., 2014). In the reconstruction of the East Asian Winter Monsoon (EAWM) variations, strong claims

70 have been drawn from changes in the rates of deposition – mass accumulation rates (MAR) - and loess
71 grain-size changes, not always without difficulties (Stevens et al., 2007). From these studies has emerged:
72 (i) the general claim of a strengthening of the EAWM during glacial stages with a significant downturn of
73 EAWM activity during interglacial stages (e.g. Stevens et al., 2007; Hao et al., 2012; An et al., 2014); and
74 (ii) the recognition of more short term stadial-interstadial to millennial scale events (Porter and An,
75 1995; Sun et al., 2010, 2011; An et al., 2014).

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

83

84 These palaeoclimate interpretations of the significance of inferred winter loess depositional rates and
85 grain size changes have been recently cast into doubt by claims that the record of dust events in the
86 Chinese loess succession does not relate to a stronger EAWM (Roe, 2009; Lu et al., 2011). The claims
87 have now entered the more general literature (Williams, 2014:153) and challenge a vast research effort
88 with far-reaching implications for our understanding of global scale climate teleconnections and drivers.
89 Roe's (2009) claims are based on the fact that present-day dust events occur in spring and hence do not
90 relate to or indicate winter synoptic states. Roe (op. cit.) recognises that such dust events are driven by
91 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.

114 At 200 hPa, the Polar East Asian Jet is prominent, with its maximum located just southeast of Japan. The
115 Polar Jet is associated with strong baroclinic instability, large vertical wind shear and cold air advection.

116

117 The cold air ‘excursions’, also described as ‘cold surges’, are channeled by the trough southwards and are
118 a characteristic feature of the EAWM (Lau and Chang, 1987) that impact strongly on the winter climate
119 of eastern China. Their path is in part related to relief controls of the Tibetan Plateau, with their effect
120 extending to the tropics, where they can lead to the flare-up of convective activity over the Maritime
121 Continent (Chan and Li, 2004). The recognition of cold-surges as a meteorological feature extends back
122 to the early part of the last century (Li, 1937; Lu, 1937). They were then termed ‘cold waves’ and were
123 recognised as being associated with ‘sandstorms’ (Lu, 1937). Lu (op.cit.) described an event in March
124 1936, which could be traced over much of east China extending into the south and associated with a
125 regionally extensive sandstorm.

126

127 It is now recognised that the frequency of cold-surges can act as a surrogate for the strength of the
128 EAWM (i.e. surface pressure) (Zhang et al., 1997; Ding and Sikka, 2006). For the period 1979 to 1995,
129 Zhang et al. (1997) found an average annual occurrence of 13 cold surges per year based on the
130 NCEP/NCA reanalysis data. Using different criteria, Chen et al. (2004) proposed that about 17 events
131 occur every winter. Cold surges can last from 5 to 14 days (Zhang et al., 1997), hence forming a
132 significant component of the winter climate of the southern East Asia – South China Sea region. But cold
133 surges do not necessarily constitute dust depositional events, as emphasised by Roe (2009). In the present
134 climate, the frequency of large-scale Asian dust events peaks between March and May (Shao and Dong,
135 2006), with more than 85% of the annual dust storms occurring during spring (Zhu et al., 2008). The
136 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

160 number of days between March and May in which a dust event is observed. Zhou et al. (2006) provide a
161 detailed introduction to these data-sets.

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163

164 **3. Results**

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

169

170 In order to provide more details on the likely relationship between dust and cold-surge events, ‘strong’
171 (>0.7) and ‘weak’ (<-0.7) CWFI years were selected and composite analyses of the corresponding dust
172 events in the following spring were carried out. The composite analyses confirm a significant
173 correspondence between the winter cold surges and spring dust events. The results clearly show that the
174 CWFI and dust frequency are positively correlated, making it evident that when the winter cold surge
175 frequency in northern China is high, then the following spring dust event frequency is also high (Fig. 3).

176

177 **4. Discussion**

178 The circulation controls of matching high (low) dust/strong (weak) CWFI events are highlighted by the
179 difference in the spring 500 hPa geopotential height and spring sea level pressure between ‘strong’ and
180 ‘weak’ CWFI years (Fig. 4). In comparing the two composites, the deepening of the Aleutian Low is
181 prominent and in strong CWFI years, the East Asian Trough is on average, 20 gpm lower, with surface
182 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 Figure 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 (Panagiotopolous 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

206 progressive weakening of the Siberian High by 12 ka, with this trend continuing into the Holocene. From
207 the model results and the present day relationship between the strength of the Siberian High, cold surges
208 and dust events, the inference of an increase in the frequency of cold surge events during glacial stages
209 follows.

210
211 Given the clear association of dust events and the strength of the Siberian High (i.e. the EAWM), it
212 follows that glacial (interglacial) stages were characterised by high (low) loess mass accumulation rates
213 (MAR), possibly associated with coarser (finer) loess grain-sizes (e.g. Kohfeld and Harrison, 2003;
214 Stevens et al., 2007; Sun et al., 2011; Kang et al., 2013; An et al., 2014). In providing a more secure
215 chronology, Kang et al. (2015) have been able to give more refinement to these claims. They demonstrate
216 that despite significant variations, all sites considered by them show increased MARs during ~26 to 19 ka,
217 with notable peaks in some stratigraphic successions during 23 to 19 ka. Generally lower MARs were
218 recognised for the time period, 19 to 12 ka. These results show a general correspondence with the strength
219 of the model reconstruction of the Siberian High (Fig. 6), with decreasing strength of the Siberian High
220 corresponding to lower MARs. In this it should not be overlooked that land surface characteristics can be
221 a control on dust entrainment and that this may be reflected in MARs. For instance, the distribution of
222 frozen ground at the Last Glacial Maximum (Liu and Jiang, 2016) is likely to have had an impact on
223 entrainment rates and hence the ‘matching’ MARs of some loess successions.

224
225 While our model results point to a strengthening of the Siberian High during glacial stages and hence a
226 stronger EAWM, the degree to which this can be expected to be apparent in loess grain-size variations
227 may not always be straightforward. It is generally recognised in the Chinese loess literature that grain-size
228 characteristics are related to source controls, transport paths and wind strength (e.g., Pye, 1987, cited in

229 An et al., 2014) But despite these complexities, a strong claim exists for a link between the grain-size
230 characteristics of Chinese loess and the strength of the EAWM (summary in An et al., 2014: 54-57). The
231 potential importance of such claims is highlighted by the recent findings of Sun et al. (2011). Using the
232 Gulang and Jinguan loess successions, they argue that grain-size variations over the last ~60,000 years
233 reflect changes in the strength of the EAWM and draw the conclusion that Atlantic meridional
234 overturning imprints itself on the EAWM through changes in the westerly circulation that ‘transmits’ this
235 signal from the North Atlantic to the EAWM region (Sun et al., 2011). These are very important
236 inferences that stress the need for focused field and climate modeling work, specifically addressing the
237 questions of the controls of loess grain-size. A need that is further emphasised by the recent Nie et al.
238 (2015) claim of the link between Yellow River sediment sources and the development of the Chinese
239 Loess Plateau.

240

241 **5. Conclusions**

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

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265 **References**

266

267 An, Z., Liu, T., Lu Y., Porter, S.C., Kukla, G., Wu, X. and Hua, Y., 1990. The long-term paleomonsoon
268 variation recorded by the loess-paleosol sequences in central China. *Quaternary International* 7/8, 91-95.
269 An, Z., Sun, Y., Zhou, W., Liu, W., Qiang, X., Wang, X., Xian, F., Cheng, P. and Burr, G.S., 2014.
270 Chinese loess and the East Asian monsoon, in: An, Z. (Ed.), *Late Cenozoic climate change in Asia: loess,
271 monsoon and monsoon-arid environment evolution. Developments in Palaeoenvironmental Research* 16.
272 Springer, Heidelberg, pp. 231–43.

273 Chang, C.-P. and Lu, M.-M., 2012. Intraseasonal predictability of Siberian High and East Asian Winter
 274 Monsoon and its interdecadal variability. *Journal of Climate*. 25, 1773–1778. DOI: 10.1175/JCLI-D-11-
 275 00500.1

276 Chang, C.-P., Wang, Z. and Hendon, H., 2006. The Asian winter monsoon, in: Wang, B. (Ed.) *The Asian*
 277 *Monsoon*, Praxis-Springer, Berlin, Heidelberg, pp. 89–127.

278 Chan, J.C.L. and Li, C., 2004. East Asian winter monsoon. In: Chang, C.-P. (ed.) *The East Asian*
 279 *Monsoon*, World Scientific Singapore, pp. 54–106.

280 Chen, T.-C, Huang, W.-R. and Yoon, J.-H., 2004. Interannual variation of the east Asian cold surge
 281 activity. *Journal of Climate*. 17, 401–413.

282 Denniston, R.F, Wyrwoll, K.-H, Asmerom, Y., Polyak, V.J., William F. Humphreys, W.F. Cugley, J.,
 283 Woods, D., LaPointe, Z., Peota, J. and Greaves, E., 2013. North Atlantic forcing of millennial-scale Indo-
 284 Australian monsoon dynamics during the Last Glacial period. *Quaternary Science Reviews*. 72, 159 –168.
 285 doi.org/10.1016/j.quascirev.201304.012.

286 Ding, Z.L., Derbyshire, E., Yang, S.L., Yu, Z.W., Xiong, S.F. and Liu, T., 2002. Stacked 2.6-Ma grain
 287 size record from the Chinese loess based on five sections and correlation with the deep-sea $\delta^{18}\text{O}$ record.
 288 *Palaeoceanography*. 17, 1–21.

289 Ding, Z.L., Rutter, N., Han, J. and Liu, T., 1992, A coupled environmental system formed at about 2.5
 290 Ma in East Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 94 (1-4), 223-242.

291 Ding, Y. and Sikka, D.R., 2006. Synoptic systems and weather, in: Wang, B. (Ed.) *The Asian Monsoon*,
 292 Springer/Praxis, Chichester, pp. 131–194.

293 Gong, D.-Y., Mao, R. and Fan, Y.-D., 2006. East Asian dust storm and weather disturbance: possible
 294 links to Arctic Oscillation. *International Journal of Climatology*. 26, 1379–1396. DOI:10.1002/joc. 1324.

295 Gong, D.-Y., Wang, S.-W. and Zhu, J.-H., 2001. East Asian winter monsoon and Arctic Oscillation.
 296 Geophysical Research Letters. 28, 2073–2076.

297 Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan,
 298 B.Y. and Lu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in
 299 China. *Nature*. 416,159–163.

300 Hao, Q., Wang, L., Oldfield, F., Shuzen, P., Qin, L., Song, Y., Xu, B., Qiao, Y., Bloemendal, J. and Guo,
 301 Z. 2012. Delayed build-up of Arctic ice sheets during 400,000-year minima in insolation variability.
 302 *Nature*. 490, 393–396. doi:10.1038/nature11493

303
 304 He, F., Shakun, J.D., Clark, P.U., Carlson, A.E., Liu, Z., Otto-Bliesner, B.L., and Kutzbach, J.E., 2013.
 305 Northern Hemisphere forcing of Southern Hemisphere climate during the last deglaciation. *Nature*. 494,
 306 81–85.

307 Heller, F. and Liu, T.S., 1984. Magnetism of Chinese loess deposits. *Geophysical Journal of the Royal*
 308 *Astronomical Society* 77(1), 125–141.

309 Jhun, J.-G. and Lee, E.-J., 2004. A new East Asian Winter Monsoon index and associated characteristics
 310 of the winter monsoon. *Journal of Climate*. 17, 711–726.

311 Kang, S., Wang, X. and Lu Y., 2013. Quartz OSL chronology and dust accumulation rate changes since
 312 the Last Glacial at Weinan on the southeastern Chinese Loess Plateau. *Boreas*. 42, 815–829.
 313 10.1111/bor.12005.

314 Kang, S., Roberts, H.M., Wang, X., An, Z. and Wang, M., 2015. Mass accumulation rate changes in
 315 Chinese loess during MIS 2, and asynchrony with records from Greenland ice cores and North Pacific
 316 Ocean sediments during the Last Glacial Maximum. *Aeolian Research* (in press).
 317 <http://dx.doi.org/10.1016/j.aeolia.2015.05.005>.

318 Kohfeld, K.E. and Harrison, S.P., 2003. Glacial-interglacial changes in dust deposition on the Chinese
 319 Loess Plateau. *Quaternary Science Reviews*. 22, 1859–1878.
 320 Kukla, G., 1987, Loess stratigraphy in China. *Quaternary Science Reviews* 6 (3-4), 191-219.
 321 Lau, K.-M. and Chang, C.P., 1987. Planetary scale aspects of the winter monsoon and atmospheric
 322 teleconnections, in: Chang, C.P. and Krishnamurti, T.N. (Eds.) *Monsoon Meteorology*, Oxford University
 323 Press, New York, pp. 161–202.
 324 Li, S.-Z., 1954, *Die Kaelteenbrueche in Ostasien*. *Collected Scientific Papers Meteorology 1919 -1949*.
 325 Academia Sinica Peking China, 15-99. (Originally published in *Meteorologische Zeitschrift* 53, 74-76,
 326 1936.
 327 Li, Y. and Yang, S., 2010. A dynamical index for the East Asian Winter Monsoon. *Journal of Climate*. 23,
 328 4255–4262. DOI: 10.1175/2010JCLI3375.1.
 329 Liu, T. and Ding, Z., 1998. Chinese loess and the palaeomonsoon. *Annual Reviews in Earth Planetary*
 330 *Sciences* 26, 111–145.
 331 Liu, Y. and Jiang, D., 2016. Last glacial maximum permafrost in China from CMIP5 simulations.
 332 *Palaeogeography, Palaeoclimatology, Palaeocology*. 447, 12-21.
 333 Liu, Z., Otto-Bliesner, B.L., He, F., Brady, E.C., Tomas, R., Clark, P.U., Carlson, A.E., Lynch-Stieglitz,
 334 J., Curry, W., Brook, E., 2009. Transient Simulation of Last Deglaciation with a New Mechanism for
 335 Bølling-Allerød Warming. *Science*. 325, 310–314.
 336 Lu, A., 1954, *Cold waves of China*. *Collected Scientific Papers Meteorology 1919 -1949*. Academia
 337 Sinica Peking China, 137-161 (Originally published in *Memoirs of the National Institute of Meteorology*
 338 10, 1937.

339 Lu, H., Mason, J.A., Stevens, T., Zhou, Y., Yi, S., and Miao, X., 2011. Response of surface processes to
340 climatic change in the dunefields and Loess Plateau of North China during the Late Quaternary. *Earth*
341 *Surface Processes and Landforms*. 36, 1590–1603.

342 Ma, X., Ding, Y., Xu, H., He, J., 2008: The relation between strong cold waves and low-frequency waves
343 during the winter of 2004/2005, *Chinese J. Atmos. Sci.*, 32(2), 380–394.

344 Panagiotopoulos, F., Shahgedanova, M., Hannachi, A. and Stephenson, D.B., 2005. Observed trends and
345 teleconnections of the Siberian High: a recently declining center of action. *Journal of Climate*. 18, 1411–
346 1422.

347 Nie, J., Stevens, T., Rittner, M., Stockli, D., Garzanti, E., Limonta, M., Bird, A., Ando, S., Vermeesch,
348 Saylor, J., Lu, H., Brecker, D., Hu, X., Liu, S., Resentini, A., Vezzoli, G., Peng, W., Carter, A., Li, S., and
349 Pan, B., 2015. Loess Plateau storage of northeastern Tibetan-derived Yellow River sediment. *Nature*
350 *Communications* 6:8511 DOI:10.1038, 1-8.

351 Park, T.-W., Ho, C.-H. and Yang, S., 2011. Relationship between the Arctic Oscillation and Cold Surges
352 over East Asia. *Journal of Climate*. 24, 68–83. DOI: 10.1175/2010JCLI3529.1.

353 Porter, S.C. and An, Z., 1995. Correlation between climate events in the North Atlantic and China during
354 the last glaciation. *Nature*. 375, 305–308.

355 Pye, K., 1997, *Aeolian dust and dust deposits*. Academic Press, 1-334.

356 Roe, G., 2009. On the interpretation of Chinese loess as a palaeoclimate indicator, *Quaternary Research*.
357 71, 150–161.

358 Shao, Y. and Dong, C.H., 2006. A review on East Asian dust climate and monitoring. *Global and*
359 *Planetary Change*. 52, 1–22.

360 Stevens, T., Thomas, D.S.G., Armitage, S.J., Hannah R., Lunn, H.R. and Lu, H., 2007. Reinterpreting
361 climate proxy records from late Quaternary Chinese loess: a detailed OSL investigation. *Earth Science*
362 *Reviews*. 80, 111–136.

363 Sun, J., Zhang, M. and Liu, T., 2001. Spatial and temporal characteristics of dust storms in China and its
364 surrounding regions, 1960-1999. *Journal of Geophysical Research*. 106, D10: 10325–10333.

365 Sun, Y., Clemens, S.C., Morrill, C., Lin, X., Wang, X. and An, Z., 2011. Influence of Atlantic meridional
366 overturning circulation on the East Asian winter monsoon. *Nature Geoscience*. 5, 46–49. E DOI:
367 10.1038/NGEO1326.

368 Sun, Y., Wang, X., Liu, Q. and Clemens, S.C., 2010. Impacts of post-depositional processes on rapid
369 monsoon signals recorded by the last glacial loess deposits of northern China. *Earth and Planetary*
370 *Science Letters*. 289, 171–179.

371 Wang, L., Li, J., Lu, H., Gu, Z., Rioual, P., Hao, Q., Mackay, A.W., Jiang, W., Cai, B., Han, J. and Chu,
372 G., 2012. The East Asian winter monsoon over the last 15,000 years: its links to high-latitude and tropical
373 climate systems and complex correlation to the summer monsoon. *Quaternary Science Reviews*. 32, 131–
374 142. doi:10.1016/j.quascirev.2011.11.003.

375 Wang, Z., and Ding, Y., 2006. Climate change of the cold wave frequency of China in the last 53 years
376 and the possible reasons, *Chinese J. Atmos. Sci.*, 30(6), 14–22.

377 Wei, J.-H. and Lin, Z.-H., 2009. The leading mode of wintertime cold wave frequency in northern China
378 during the last 42 years and its association with Arctic Oscillation. *Atmospheric and Oceanic Science*
379 *Letters*. 2, 130–134.

380 Williams, M.A.J., 2014. *Climate change in deserts: past, present and future*. Cambridge University Press.
381 629pp.

382 Wu, B. and Wang, J., 2002. Possible impacts of winter Arctic Oscillation on Siberian High, the East
383 Asian Winter Monsoon and sea-ice extent. *Advances in Atmospheric Science*. 19, 297–320.
384

385 Wyrwoll, K.-H., Liu, Z.Y., Chen, G.S., Kutzbach, J.E. and Liu, X.D., 2007. Sensitivity of the
386 Australian summer monsoon to tilt and precession forcing. *Quaternary Science Reviews*. 26, 3043–3057.

387 Zhang, Y., Sperber, K.R. and Boyle, J.S., 1997. Climatology and interannual variation of East Asian
388 winter monsoon: result from the 1979-95 NCEP/NCAR reanalysis. *Monthly Weather Reviews*. 125,
389 2605–2619.

390 Zhou, Z., Zhang, G., Ai W., Zhang, H., Niu, R., 2006. Time Series of Spring Dust Emission and Its
391 Correlative Climatic Factors in Northern China. *Journal of Desert Research*, 26 (6): 935-941.
392

393 Zhu, C., Wang, B. and Qian, W., 2008. Why do dust storms decrease in northern China concurrently with
394 the recent global warming? *Geophysical Research Letters* 35, L18702, doi:10.1029/2008GL034886.
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Figure 5: Conceptual representation of the synoptic expression of strong EAWM years promoting cold surges and the incidence of dust events over northern China.

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

Figure 1

Figure 2

Figure 3

Figure 4

(a) 500 hPa geopotential height (unit: gpm)

(b) sea level pressure (unit: hPa)

Figure 5

Figure 6