# Explaining and replies to the comments and suggestions

Ms. Ref. No.: cp-2017-50

Title: Environmental dynamics since the last glacial in arid Central Asia: evidence from grain size distribution and magnetic properties of loess from the Ili Valley, western China

Following parts are our explanations what changes to the manuscript have made and how our replies (Answer or Reply, A&R, Black) to the reviewer's comments (comments and suggestions, C&S, Blue).

***Replies to the comments of Dr. Vandenberghe***

For *General Comments*

**C&S**: Many studies deal with the correspondence between loess deposits and climate circulation but the causal relations are indeed poorly understood. Previously, the attention has been drawn to competing circulation systems of westerlies and monsoons. Thus, relations are indeed best studied in a region where different systems could have been present at times. Consequently, the studied region is favorably situated for this timely research. A most interesting result is the importance of precipitation on the loess depositional signal. Until now most attention has been paid to temperature variability that of course also impacts the wind circulation. It seems by this study that resulting oscillations in loess deposition show a complex pattern. And this may be the reason for the fact that the oscillating loess signals in C. Asia and the NE Tibetan Plateau are not that simply correlated with D-O-events or H-events. The paper is well written, designed and archived.

**A&R**: Thanks for your positive comments. This paper made aims to investigate the causal relations between loess deposits and climate circulation. Recently, many researchers have paid much attention to paleoclimate reconstruction in transitional regions where different atmospheric systems predominate at different times, e.g. the Central Balkans (Ramisch et al., 2016), the Qinghai Lake region (Cheng et al., 2012), southwest Asia (Hamzeh et al., 2015). Our study area is likewise situated in the zone influenced by different climatic systems. It therefore becomes important prerequisite to clarify the paleoenvironmental significance of various proxies, in particular which proxies reflect temperature, which represent precipitation, and which indicate wind strength. Our manuscript explores the potential impacts of precipitation on the loess depositional signal, and identifies areas where more work needs to be done in the future.

We agree that some scientists have focused on the influence of temperature variability on wind circulation, and in particular the role of local insolation minima in driving an early onset of the LGM in the Southern Hemisphere (Vandergoes et al., 2005). We reconsider the reasons for variations in EM1 proportions, and suggest that the availabilities of source sediments which are likely impacted by development of permafrost and vegetation growth in dust source areas, are responsible for the weaker EM1 proportion fluctuations in LGM and early-MIS3. Please see the details in line 464-470 and 504-509 of revised manuscript. The aeolian loess sediments in Central Asia are more likely to respond to a complex mixture of global signals with local insolation, glacial activity and local weathering. This overlap will weaken the global signals as preserved within the loess.

For *Minor Comments*

**C&S**: L 343-359: Two different explanations are claimed for the origin of the fine-grained endmember 3 (c. 18.9 μm). The main difference seems to be, if I understand well, that one hypothesis invokes high-suspension transport while in the other one surface winds are involved. However, both hypotheses interpret that this component is the result of background loess supply (as confirmed in lines 389-395) as previously demonstrated by Prins et al (2007), Vriend et al (2011) and Zhang et al (1999). It is not realistic to separate the grain-size fractions of 2-8 μm (transported by westerlies) and 8-15 μm (=EM3, transported at low altitude) as the authors seem to do. Both components react jointly constituting background loess supplied by westerlies as described by e.g. Prins et al. (2007).

**A&R**: We agree with the reviewer on this point. The origins of the EM3 size fraction is indeed complex. For example, based on modern dust monitoring from the high-altitude subtropical Puna-Altiplano Plateau in South America, Gaiero et al. (2013) found that “Finer mode dust is deposited during event periods, which point to a dominant long-range transport, contrasting with a dominance of coarser mode observed for non-dust sampling periods, pointing to dominant local sources.” Prins and Vriend (2007) and Prins et al. (2007) suggested that the clayed loess component represented the fine dust component supplied over the entire Loess Plateau by long-term suspension processes, and the high-level subtropical jet stream (westerly winds) might, at least partly, be responsible for the input of this fine-grained loess component. End-member unmixing results of Xiaoerbulake (XEBLK) loess (Li et al., 2016b) grain-size distributions show the similar EM3 component to NLK loess (Fig. R1). XEBLK loess section is also located in the Ili Baisn. That implies that the fine-grained EM3 (c. 18.9 μm) is the result of background loess supply in the Ili Basin regardless of its origin (Vriend et al., 2011;Zhang et al., 1999;Prins et al., 2007). It is difficult to determine the origins of the fine silt/clay. The appearance of the fine component in dust deposition may be caused by aggregation, due to fine particles adhering to the coarse particles, as well as chemical weathering. Perhaps the method of Machalett et al. (2008) is the better alternative. They neither removed organic matter and carbonates from the stratigraphic samples and nor applied an intensive ultrasonic treatment to disaggregate particles.

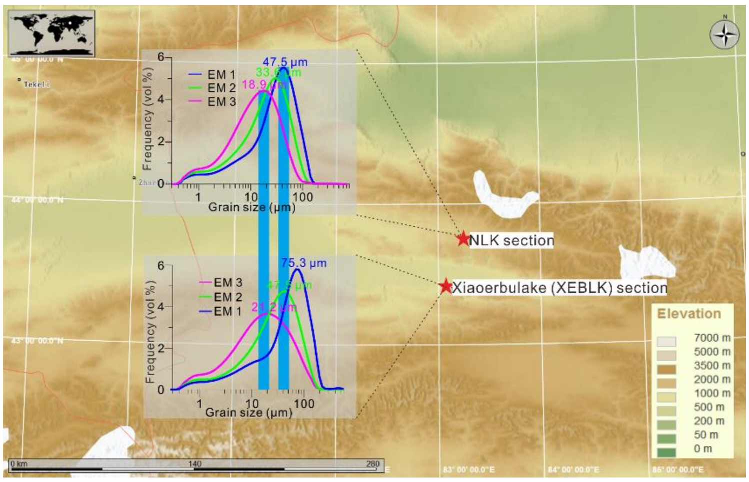


Fig. R1 Comparison of end-member unmixing results of NLK loess and Xiaoerbulake (XEBLK) loess grain-size distributions.

**C&S**: L 441-447: If the Ili valley is sheltered from northeastern wind, as the authors claim, what is then the source area for the EM1 and EM2 fractions? There is no apparent difference between these coarse-grained fractions on the CLP, N Tibet Plateau and in the Ili valley where a distinct supply is clear from the northeast under the influence of the Siberian High.

**A&R**: Thank you for this suggestion. The northern Tien Shan Range reaches altitudes of > 4000 m a.s.l. For the particles with grain size of > 20 µm, it is unlikely that grains of this coarser silt fraction were transported by north-easterly winds above the 4000 m altitude over the northern Tien Shan and into the Ili Basin. We therefore interpret the coarser grained loess particles in the Ili Basin to have been predominantly transported by near-surface winds. The topographic context (Fig. 1 in revised manuscript) most likely ensured the westerly winds coming to be the transporting agent. Moreover, we added modern meteorological data (2009-2013) in NLK in the *Supplementary file*. It was evident that the strongest winds at NLK site mainly blowed from the west.
In our speculation as to the provenance of the NLK loess, we initially compared the REE parameters of NLK loess with those of desert sands and modern soils from the Ili Basin and further west into Kazakhstan (Fig. R2). Our results indicated that the deserts and topsoils in Kazakhstan are unlikely to be the main potential source areas. In contrast, topsoils from the Ili Basin probably provide the most important source materials in the NLK loess. The Quaternary sediments of the Ili Basin mainly consist of alluvial fans and floodplains, and the top soils developed on those. We therefore speculate a proximal source for the NLK loess. Furthermore, recent work from our group indicates that size-differentiated rare earth elements (REE) may help to distinguish potential proximal or distal sources (Chen et al., 2017). In future, we expect to find more substantial evidence for tracing loess provenance in the region.

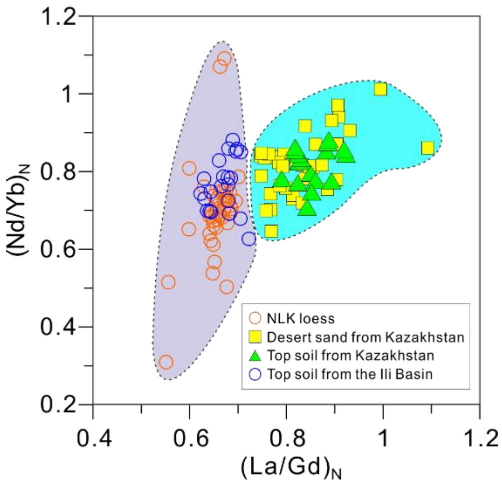


Fig. R2 $(Nd/Yb)_N$ vs. $(La/Gd)_N$ of loess, top soil and desert sands from the Ili Basin and Kazakhstan.

**C&S**: L 454-456: Explain better how the ‘cyclonic storms’ originated by protrusion of the Arctic polar front, rather than by other circulation patterns.

**A&R**: This is a constructive question. We have reconsidered this issue. We have collected some modern and Holocene records about atmospheric circulation in Central Asia over the past month, and exclude the influences of the Arctic polar front and assure the importance of the Siberian High for dust transport and increased loess accumulation at NLK.

Available data enable us to compare our data from the eastern, sheltered end of the Ili Basin with the Remizovka section at the southwestern margins of the basin – with respect to likely climatic influence and its impact on grain size. Remisowka (Machalett et al., 2008) is located along the northern piedmont of Tianshan Mountains (Fig. 1a in manuscript). Because NLK site is much more sheltered from northerly weather systems than Remisowka, there is a good chance that the polar front had more of an influence on Remisowka than on NLK. While in the north/northeast of our study area is a massive cold high — Siberian High. The Siberian High is the most dominant Northern Hemisphere anticyclone and is centered between 40°N and 65°N, 80°E and 120°E (cf. Fig. 3 in Huang et al. (2011)), and its anticyclonic feature is broadly recognized as the dominant mode of winter and spring climate over Eurasia (Sahsamanoglou et al., 1991;Savelieva et al., 2000;Panagiotopoulos et al., 2005;Gong and Ho, 2002). In addition, based on modern and Holocene climate data, we argue that the Siberian High may have exerted a significant influence on wind dynamics in the Ili Basin, leading to dust transport and the accumulation of loess during cold phases in NLK.

In addition, modern meteorological data show that the maximum wind at NLK mainly blows from the west, and that dust storm development in Ili river valley is closely linked with southward-moving high-latitude air masses, while the air masses can enter into the Ili Basin round the northern Tianshan (see the Fig. S5 in *Supplementary file* and Ye et al. (2003)). Therefore, the Siberian high-pressure system is able to influence the Ili Basin, and the southward-moving high-latitude air masses associated with it can enter into the Ili Basin, leading to dust transport and the accumulation of loess deposits during cold phases in NLK.

Also, we compare secular trends between the EM1 proportions and mean grain size data from the Jingyuan section over the last glacial period (Sun et al., 2010). It is widely acepted that increases in grain-size records from the CLP are linked to a strengthening of the East Asian winter monsoon due to an intensification of the Siberian High (Hao et al., 2012;Ding et al., 1995). The similarities in the trends can be observed (Fig. 7 in revised manuscript). For example, there remain coarser grain size and higher sedimentation rate during mid-MIS3 (Sun et al., 2010), and opposite cases occur in early- and late-MIS3. Therefore, that supports that a common Eurasian atmospheric forcing pattern — the Siberian High — is responsible for the climate evolution of these two regions during that time period. Therefore, we have rewritten the section 5.3. Please see *Lines 439-487* in the revised manuscript.

**C&S**: L 476: The interesting absence of correlation between the observed grain-size signals and N Atlantic abrupt events is not only found in the Ili valley but also previously in Tadjikistan and the NE Tibet Plateau (Vandenberghe et al. 2006)

**A&R**: That point has been attracting the attention of our group recently. We find that EM1 proportions fluctuate weaker in H2 and H5 events (Fig. 7 in the revised manuscript). We thus reconsider the reason for variations in EM1 proportions, and suggest that the availabilities of source sediments which are likely impacted by development of permafrost and vegetation growth in dust source areas, are responsible for the smaller EM1 proportions in LGM and early-MIS3. Please see the details in line 464-470 and 504-509 in the revised manuscript.

Therefore, in our view, the lack of good correlation between observed grain-size and millennial-scale Atlantic events suggests that the loess records in Central Asia represent a response not only to global signals but also local signals, such as glacial activity and local weathering. This overlap will weaken the global signals.

**C&S**: L 483-484: This sentence is not clear: is 'which' referring to the conclusions by the authors or by Vandenberghe et al.? It is not clear therefore what really is contradicting

**A&R**: I am so sorry for the poor expression. The 'which' referred to the conclusions by the authors. We have revised the sentence, like this "Darai Kalon is located in a region where the mid-latitude westerlies clearly have a much stronger influence, especially during full glacial conditions (Vandenberghe et al., 2006). In contrast, our results from the Ili Basin suggest that the mid-latitude westerlies did not always predominate north of the Kyrgyz Tian Shan due to northward or southward movement of the climate subsystem. In this case, the high mountains in Central Asia most likely obstructed the migration of the Asiatic polar front further south towards Tajikistan where those data were derived (Machalett et al., 2008), thereby resulting in a stronger westerlies signal at Darai Kalon than at NLK." The movement northward or southward of mid-latitude westerlies makes the Ili Basin more sensitive to paleoclimate change in Central Asia, which establishes the strategic position of the Ili Basin in paleoclimatic reconstruction.
However, as we mentioned above, the Siberian high-pressure systems predominate in the Ili Basin during cold phases, leading to dust transport and increased loess accumulation at NLK, and our grain-size proxy data can also correlate with abrupt events, such as Heinrich events (H1 to H6) identified from the North Atlantic records, though EM1 proportions fluctuate weaker in H2 and H5 events. Therefore, we have revised this section.

For *Technical comments*

**C&S**: L 123: 'more reliable' than what?

**A&R**: Thank you for your careful reading. We have rewritten this sentence. Actually, we mean that the optically stimulated luminescence (OSL) dating is more reliable for constructing a loess chronology than AMS $^{14}$C ages for older than MIS2 aeolian sediments according to Song et al. (2015).

**C&S**: L 317: 'shorter' than what?

**A&R**: EM1 is likely derived from shorter distance transport of suspended load owing to its larger modal grain size. Thus, its transport distance is shorter than the finer grains, like the EM2 and EM3 fractions in this manuscript.

**C&S**: L 139: insert 'were' between 'S1)' and 'then'; Figure 1 is too small.
L 182: remove 'are';
L 513: remove 'can' or 'may'.

**A&R**: Yes, these are grammar errors. We have corrected these mistakes accordingly. We also adjusted the layout of Fig. 1 and increased front size. Thank you.

**C&S**: I suggest to shorten the title a bit

**A&R**: Yes, we have rewritten the title, "Aeolian dust dispersal patterns since the last glacial period in eastern Central Asia: Insights from a loess-paleosol sequence in the Ili Basin". Thank you.

**C&S**: Dear authors, I agree with most of your replies and thank you for the modifications. I just want to react with 2 comments: 1. To the origin of the very fine silt-clay component: Chemical weathering is indeed a good candidate as measured by Konert and Vandenberghe 1997, and well-illustrated by the experiments of Sun YB et al 2006. Transport as aggregates of fines by monsoonal dust storms (Qiang et al 2010) is contradicted by their very widespread and general occurrence (Vandenberhe 2013). Adherence of fines to larger grains has been contradicted by several authors. 2. Provenance of EM 1-2: I agree with your explanation. I understand now that you also agree with a northern wind, however not crossing the high mountains to the north but carrying dust only at low elevation over short distance. In my opinion, the carrying agent may still be the northern monsoonal wind, although restricted to the Ili basin.

**A&R**:

1. The complexity of finer component is reflected in not only its origin but also uncertainty of instrument measurement (Ujvari et al., 2016;Mason et al., 2011). Chemical weathering can efficiently decrease gain size of loess (or paleosol) through the transformation of feldspar minerals into clay minerals linked closely to the process of pedogenesis. Sun et al. (2011) regarded this component formed by pedogenesis "ultrafine component". However, we have investigated clay mineralogy of NLK loess section, and the results show that the major clay mineral components in the NLK section were illite, chlorite, kaolinite and smectite, and that those clay minerals mainly had detrital origin, and rather than are in-situ weathered products. Moreover, variations in illite contents along the NLK section may be controlled by wind intensity, because weaker wind intensity would transport more fine fractions, which was supported by the wind tunnel experiment (Wang et al., 2017). Therefore, we think the degree of influence of chemical weathering on the loess grain size depends on the differences of environment conditions from site to site. Qiang et al. (2010) suggested that formation of aggregation increased particle mass, which enabled fine grains to be deposited even under stronger winds by dry deposition, however, the aggregates had larger pores and relevant lower density than individual minerals grain of the same size. Therefore the aggregates still can be influenced by the effects of sorting by aeolian processes. However, by observing the dust deposition collected in dust storm, Lin et al. (2016) thought that particles less than 20 μm could settle down during floating dust weather when the wind velocity decreased and even stopped. Therefore, it seemed to be difficult to distinguish that the aggregates were formed after deposition or they were transported by winds directly. Observations of modern dust under the scanning electron showed the phenomena of aggregation and/or fine particles adhering to larger ones (Pye, 1995, 1987;Derbyshire et al., 1998;Falkovich et al., 2001;Qiang et al., 2010), whereas the micrographs of fresh samples from the southern margin of Tarim Basin under SEM showed little aggregation, or adhering of fine particles to the coarse particles (Lin et al., 2016). Maybe more convincing evidence will come from a lot of studies of modern storm processes.

2. Yes, we agree with you. After reconsideration as mentioned above, we suggest that the Siberian high-pressure system exerts a significant influence on wind dynamics and thus the loess deposition in the eastern Ili Basin. Therefore, we have rewritten the section 5.3. Please see *Lines 439-487* in the revised manuscript.

***Replies to the comments of anonymous Referee #2***

For *Linguistic issues*

**C&S:** Lines 37-42: A lack of correlation between EM1 proportions and GISP $\delta^{18}O$ values at the millennial scale, combined with modern weather data, suggests that Arctic polar front predominates in the Ili Basin and the Kyrgyz Tian Shan piedmont during cold phases, which leads to the dust transport and accumulation of loess deposits, while the shift of mid-latitude westerlies towards the south and north controls the patterns of precipitation/moisture variations in this region. Reviewer's note: a lack of correlation between A and B means C was dominant? It implies that there are no other possibilities (D, E, …). Even worse, is "while the shift of the mid-latitude westerlies … controls patterns of precipitation/moisture …" corresponding to or with"shift of the Arctic polar front controls the temperature patterns of wind strength"? If so, you have to say so.

**A&R:** Thanks for your critical comments. The logic of the abstract was unclear, and it is unreasonable to draw conclusions beyond the information available in the data. We have now tried to clear the confused logic, and rewritten the Abstract and Conclusions sections in this manuscript. It is important to note that Central Asia is very large and consequently it is reasonable to assume that different climate subsystems act upon different parts of the region. Therefore, observations made at one end of Central Asia (e.g. Tajikistan) do not necessarily apply to the other (e.g. Ili Basin). Furthermore, the Ili Basin itself is almost 1000 km across and is geographically diverse, and it is reasonable to assume that the western part of the basin, e.g. the published site of Remizovka, is more exposed to influences such as the polar northerlies than sites in the eastern part of the basin, e.g. NLK presented here, which are much more sheltered by the high Tien Shan mountains.

Tajikistan is mainly impacted by the westerlies, and the North Atlantic climatic signals are presented in Tajikistan loess, which implies that the westerlies linking the North Atlantic and the Eurasia loess, can influence accumulation of loess deposits in Tajikistan (Vandenberghe et al., 2006). A lack of good correlation between EM1 proportions and GISP $\delta^{18}O$ values at the millennial scale only indicates that other climate systems control the wind dynamics responsible for dust transport and the accumulation of loess during cold phases in NLK, rather than the Westerlies. Thus, we cannot conclude that "Arctic polar front predominates in the Ili Basin and the Kyrgyz Tian Shan piedmont during cold phases."

We added some records from modern and Holocene climate change records to substantiate our arguments for mid-Westerlies changes. Actually, those records demonstrated that the mid-latitude Westerlies truly controlled the patterns of moisture variations in Arid Central Asia (ACA) (Huang et al., 2015;Li et al., 2011b;Cai et al., 2017). However, we can't draw that conclusion from "A lack of correlation between EM1 proportions and GISP $\delta^{18}O$ values at the millennial scale".

"while the shift of the mid-latitude westerlies … controls patterns of precipitation/moisture …" isn't corresponding to or with "shift of the Arctic polar front controls the temperature patterns of wind strength". Available data enable us to compare our data from the eastern, sheltered end of the Ili Basin with the more exposed Remizovka section at the southwestern margins of the basin – with respect to likely climatic influence and its impact on grain size. Remisowka (Machalett et al., 2008) is located along the northern piedmont of Tianshan Mountains (Fig. 1a in manuscript). Because NLK is much more sheltered from northerly weather systems than Remisowka, there is a good chance that the polar front had more of an influence on Remisowka than on NLK. Furthermore, based on modern and Holocene climate data and comparison of the EM1 proportions and mean grain size (MGS) data from the Jingyuan section in northwestern CLP, we argue that the Siberian High may have exerted a significant influence on wind dynamics in the Ili Basin, leading to dust transport and the accumulation of loess during cold phases in NLK. Therefore, we argue that the Siberian High controls wind strength and mid-latitude westerlies control precipitation/moisture. A strengthened Siberian High would push the mid-latitude Westerlies pathways further to the south, resulting in comparably drier conditions in the northern Central Asia regions (e.g. Tianshan Mountains) but wetter conditions in south-western Central Asia (Pamir) (Lei et al., 2014;Wolff et al., 2017). Intensity and geographical position of the Siberian High can strongly control precipitation and atmospheric circulation patterns (meridional or zonal) at mid-latitudes of Asia (Panagiotopoulos et al., 2005). The coupling of the Siberian High with the mid-latitude Westerlies system likely contributed significantly to the climate variability in the study area. We have modified our text to explain these drivers more clearly, and also rewritten the *Abstract*. Please see details in the revised manuscript

**C&S**: Lines 42-44: Comparison of EM1 proportions with Northern Hemisphere summer insolation clearly illustrates local insolation-based control on wind dynamics in the region, and humidity can also influence grain size of loess over MIS3 in particular. Reviewer's note: to me (this reviewer), the logic relationship between these two sentences are not traceable at all. "local insolation-based control on wind dynamics": what does this mean?

**A&R**: We reconsider the relationships between June insolation at 45ºN and EM1 proportions in Fig. 7, and the reasons for variations in EM1 proportions. We think it is more reasonable to consider that the availabilities of source sediments which are more likely impacted by development of permafrost and vegetation growth in dust source areas, are responsible for the weaker EM1 proportion fluctuations in LGM and early-MIS3. Therefore, we have deleted the discussion of summer insolation. Please see the details in line 464-470 and 504-509 of revised manuscript.

**C&S**: Lines 55-60: The relative influence and intensity of these major climate subsystems have varied across the latitudinal and longitudinal range of Central Asia through time. Thus identification of the predominant climate regimes in a certain region is a crucial precondition for tracing paleoclimatic evolution. Reviewer's note: (1) relative influence? Maybe relative importance. (2) The first sentence continues its SPECIFIC tone (i.e., Central Asian), but the second sentence turns to a general tone (i.e., a certain region). To me (this reviewer), it is misleading.

**A&R**: (1) We have clarified this distinction in the text, and substituted "relative influence" with "relative importance". (2) We cannot use a specific concept to represent a general concept. It is indeed misleading. We have changed the second sentence to "Thus identification of the predominant climate regimes in this region, using geological archives, is a crucial precondition for tracing paleoclimatic evolution.”

**C&S**: Lines 66-72: While loess in Central Asia has (……) increasingly formed the focus of loess research, as yet the forcing mechanisms and the climatic conditions responsible for loess-paleosol sequences formation are ambiguous, and the paleoclimatic evolution recorded by these loess deposits in this region is not systematically understood. Reviewer’s note: to me (this reviewer), “increasingly formed the focus”, “the forcing mechanisms … are ambiguous”, and “not systematically understood” are all belong to“expression inadequacies”.

**A&R**: Here, we have simplified the language and made the purpose of this paper much clearer and better to understand. We also added three citations in an effort to reinforce the lack of systematic understanding of the forcing mechanisms and the climatic conditions responsible for loess-paleosol sequences formation.

**C&S**: Lines 78-81: Climatic teleconnections, especially between the North Atlantic and East Asian Monsoon regions, are likely to have been recorded within the Central Asian loess. As yet, however, the region so far largely lacks data by which the role and contribution of the central parts of the Eurasian continent, as an environmental bridge, can be elucidated. Reviewer’s note: to me (this reviewer), there is a logic gap in this statement. I mean that you (authors) may have to bring the environmental bridge to the front so that the importance of Central Asia in documenting the teleconnections is pronounced first.

**A&R**: Thanks for your suggestion. We have clarified the language in the text and the wording of our arguments. Since we know basically nothing about millennial-scale climatic changes in Central Asia, our aim is to investigate a loess section in Central Asia to see to what degree climatic teleconnections exist between North Atlantic and East Asia first, i.e. the first step is to generate data. Therefore, we have made the aim clearer, like this “Data for Central Asian loess are so far lacking at this resolution, despite its strategic location as a likely environmental bridge between the North Atlantic and East Asian Monsoon regions.” We deleted the sentence “Climatic teleconnections, especially between the North Atlantic and East Asian Monsoon regions, are likely to have been recorded within the Central Asian loess.”

**C&S**: Other suggestions Magnetic Susceptibility 1.1. “Low susceptibility in paleosols and high susceptibility in loess units” were sufficiently documented in Alaskan loess and in Siberian loess and Professor Liu Xiuming is a leading scientist on this. Please see if his works and propositions can help you. 1.2. The coarse particle-association of high susceptibility can be tested simply by measuring the susceptibility of different particle size fractions. This can be done on selected samples and the data of the selected samples may elevate your confidence of interpretation. 1.3. If I were the author, I would have completely excluded susceptibility portion from this paper and may (just may) write a separate paper on magnetic susceptibility.

**A&R**: The relationship between pedogenesis and magnetic susceptibility in the higher-latitude loess deposits of Alaska and Siberia is different from the Chinese Loess Plateau loess as suggested by Liu et al. (1999) and Liu et al. (2008). At NLK, lower susceptibility exists in paleosols and higher susceptibility in loess units. Although this scenario is difficult to explain fully through variation in wind strength alone, it showed that wind strength, or wind dynamics, would influence MS variations at least and thus paleoclimatic reconstruction using climatic proxies, such as MS. Thus it is necessary to understand the atmospheric dynamic pattern during loess deposition further.

Consistently low $\chi_{fd}$% values in both loess and paleosol layers demonstrated that the content of SP particles is very low, and consequently that their contribution to MS can be ignored. That is, weaker pedogenesis prevents the efficient production of SP grains. We hence consider that allogenetic magnetic minerals made the greater contributions to MS, and these correlate with dust transportation.

Following the reviewer's suggestions, we sieved five samples into > 63 μm, 63 – 40 μm, 40 – 32 μm, 32 – 20 μm and < 20 μm grain size fractions, and each of samples were measured at least three times using a Bartington MS2 meter. Our results showed lower MS values in > 63 μm grain size fractions and maximum values existed in 32 – 20 μm or < 20 μm grain size fractions (Table R1), which indicated that the major ferromagnetic minerals were always smaller than sand size. Therefore, we deleted the sentence "MS enhancement at NLK is primarily driven by increased concentrations of sand-sized detrital magnetic minerals" in the manuscript.

Understanding the mechanisms for the enhancement of magnetic susceptibility is beyond the scope of this study. We only intended to illustrate the significant impacts of wind dynamic on MS. In addition, ferromagnetic minerals, including magnetite and hematite, belong to heavy minerals which have higher relative density. Thus when wind becomes stronger, more ferromagnetic minerals will be transported to deposition areas, resulting to higher MS values. Thus we have modified the subtitle 5.1, like this "Impacts of wind strength on magnetic susceptibility variations".

Table R1 Magnetic susceptibility values ($10^{-8}m^3kg^{-1}$) of different grain-size fractions

| Sample No. | Grain-size Fractions | | | | |
|---|---|---|---|---|---|
| | > 63 μm | 63-40 μm | 40-32 μm | 32-20 μm | <20 μm |
| NLK400 | 72 | 66 | 86 | 88 | **98** |
| NLK800 | 67 | 61 | 80 | **87** | 85 |
| NLK1108 | 73 | 78 | 104 | 107 | **108** |
| NLK1110 | 75 | 68 | 96 | **109** | 105 |
| NLK1400 | 79 | 83 | 94 | 100 | **111** |

Note: Red font represents maximum values in different grain-size fractions.

**C&S**: Particle Size 2.1. You need a comprehensive and streamlined review on existing literature dealing with interpretation of loess particle size. The literature review can be either "school division-based" or time-based (earlier time and later time) or country based (west and China). 2.2. After the expected review is properly done, you may delete those insignificant references (I mean that you cited too many and that many of them may be insignificant). 2.3. Since you heavily rely on Vandenburghe (2013) for EM1, EM2, and EM3 arguments, you are strongly suggested to provide a complete and concise re-statement of Vandenburghe (2013) in debating pros and cons of EM1, EM2, and EM3 for representing aolian dynamics. If he was so sure and nobody else was at his odd, your application of EM1, EM2, and EM3 to interpreting aolian dynamics may be more acceptable. If his argument was case-dependent, you have a harder task to establish your case though. 2.4. I am wondering if the cumulative particle-size curve does show a statistically meaningful break between EM1 and EM2 and also a break between EM3 and EM2? If it does not, should your reliance on

Vandenburghe (2013) be questionable? What I try to say is: if you can confidently justify the acceptance of EM1, EM2, and EM3 for representing aolian dynamics, you do have a case here. Otherwise, your opponents can always argue that: those coarse particles may have indeed locally sourced, but those fine particles can either be remotely (high-elevation) sourced or locally (near-surface) sourced.

**A&R**: Thanks for your suggestions. In the section 5.2, we have summarized the significance of grain-size analysis. Relevant studies were separated into two groups according to the unmixing method of grain size spectra. Vandenberghe (2013) applied visual inspection of grain-size distribution curves and the EMMA end-member analysis in combination to define the characteristic grain-size distribution of primary loess deposits and review their respective processes and conditions of transports and deposition, relying largely on loess samples from central and eastern Asia and northwestern and central Europe. Thus his argument was based on a large number of previous studies from a range of sites, and is not case-dependent. For example, *the subgroup 1.b.2* in Vandenberghe (2013) has also been identified in the loess of Chinese Loess Plateau, southern, northwestern and central Europe. Furthermore, in the studies of loess sediments from the Qilian Mountain region, Rasmussen et al. (2014), Nottebaum et al. (2015) and Yang et al. (2016) have interpreted the multiple sources of loess sediments and dynamic conditions according to sediment groups in Vandenberghe (2013). We have included those arguments in the main text.

EM1 and EM2 of our results have modal grain size approximately corresponding to the '*subgroup 1.b.1*' and '*subgroup 1.b.2*' respectively. Vandenberghe (2013) suggested that although component 1.b.1 and 1.b.2 occur jointly together in the proximal depositional regions, they are clearly distinct from each other in terms of the coverage and transportation distance. In Fig. 4 of manuscript, the mirror image relationships over millennial scales can be observed, which may implied that both EM1 and EM2 have a same origin, but wind strength controlled the relative proportions of both through time. In addition, grain-size distributions of modern dust illustrate a modal grain size of 33.3 μm in winter and 44.6 μm in summer in the northern and western Chinese Loess Plateau (Sun et al., 2003) (Fig. R3). These modes are similar to EM2 and EM1 in our results, respectively. It is generally assumed that vegetation coverage is more extensive in summer than in winter in CLP. Therefore, availability of sediments in source areas wouldn't influence the grain sizes, conversely differences in wind dynamic between these two seasons likely play an important role in controlling the grain sizes. While EM3 ("*subgroup 1.c.1*") indicated a different aerodynamic environment from EM2. The former would settle when the wind velocity decreases and even stops, as suggested by Lin et al. (2016), but the latter were interpreted as transportation during cyclonal dust storm outbreaks (Vandenberghe, 2013). Consequently, the cumulative particle-size curve can give a statistically meaningful break between EM1 and EM2 and also a break between EM3 and EM2.

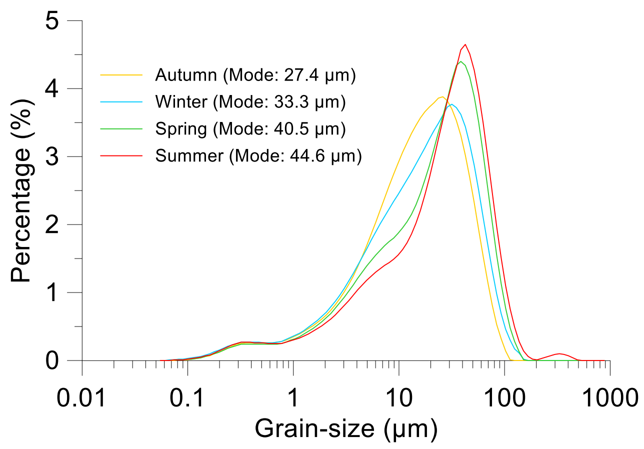


Fig. R3 Grain-size distributions of seasonal dusts in the northern and western CLP (Huanxian)

Actually, greater dispute exists in the origin of the EM3 size fraction. In the manuscript, we suggest that the fine-grained EM3 (c. 18.9 μm) is the result of background loess supply in the Ili Basin, and infer the EM3 modal peak to derive from low altitude non-dust storm processes after excluding the aggregate model, transportation by high-altitude westerlies and influences of post-depositional processes. Therefore, those fine particles are also likely to be locally (near-surface) sourced.

**C&S**: Questions for 5.3 Aeolian dust dynamics in eastern Central Asia: links to atmospheric systems Lines 440-447: Central Asia is variably influenced by the Asian monsoon from the south (Dettman et al., 2001; Cheng et al., 2012), the mid-latitude westerlies (Vandenberghe et al., 2006), the Siberian high-pressure systems from the northeast (Youn et al., 2014), and the polar front from the north (Machalett et al., 2008). However, by virtue of its geographical position, most of these climate influences can be excluded for the Ili Valley since it is sheltered to the northeast, east and south. The Asian high mountains largely inhibit the intrusion of Asian (Indian and East Asian) monsoons to the region, and the influence of the Siberian High (An, 2000) has been shown to decrease westward from the CLP (Vandenberghe et al., 2006). Reviewer's note: Downplaying Asian monsoons may be acceptable since the Yili Valley is indeed blocked by the Tianshan Mountains on the south. But, downplaying Siberian high-pressure system (SibH) is not well justified. Yes, SibH is weakening away from its center, but you cannot say that the Yili Valley was beyond the SibH influence. Furthermore, your favored "polar front" is actually also blocked by high mountains on the north. If polar front was indeed the major player, you may have to provide modern climate backgrounds in which strong polar front interacted with the prevailing westerly flow to stimulate dust storms in the Yili Valley.

**A&R:** Thanks for your good suggestions. As described above, the Siberian high-pressure systems predominate in the Ili Basin during cold phases, which leads to dust transport and increased loess accumulation at NLK, and the mid-latitude Westerlies controlled broad-scale patterns of moisture variation across ACA.

Modern meteorological data show that the maximum wind at NLK mainly blows from the west, and that dust storm development in Ili river valley is closely linked with southward-moving high-latitude air masses, while the air masses can enter into the Ili Basin round the northern Tianshan (see the Supplementary materials and Ye et al. (2003)). Therefore, the Siberian high-pressure system is able to influence the Ili Basin, and the southward-moving high-latitude air masses associated with it can enter into the Ili Basin, leading to dust transport and the accumulation of loess deposits during cold phases in NLK. The coupling of the Siberian High with the mid-latitude Westerlies system likely contributed significantly to the climate variability at NLK in the eastern Ili Basin.

We have rewritten the section 5.3. Please see the details in the revised manuscript and Supplementary materials.

**C&S**: Lines 448-456: Modern satellite data indicates that dust storm development in Ili river valley is closely linked with southward-moving high-latitude air masses (Ye et al., 2003). Karger et al. (2016) provided a detailed picture of the westerlies for the Ili Basin, in which a rain belt gradually migrated towards the south and north in autumn and summer, respectively. According to this scenario, enhanced evaporation coupled with strengthened westerly winds would bring more humid and warm air masses to Arid Central Asia (ACA) during the Holocene (Zhang et al., 2016). Therefore, based on our grain-size observations, we argue that the Arctic polar front, intruding southward in the winter and retracting northward in summer (Machalett et al., 2008), most likely increased the frequency and strength of cyclonic storms, leading to dust transport and the accumulation of loess deposits during cold phases when it predominated in the Ili Basin and along the Kyrgyz Tian Shan piedmont. Reviewer's note: I (this reviewer) failed to see the linkage between "souward-moving high-latitude air masses" and "migrated rain belt". I also failed to see the linkage between "enhanced evaporation" and "strengthened westerly winds". Consequently, I failed to see the logic of your reasoning: the Arctic polar front, intruding southward in the winter and retracting northward in summer (Machalett et al., 2008), most likely increased the frequency and strength of cyclonic storms during cold phases. At least, you have to say more about the logic of your reasoning.

**A&R:** In this respect our logic was flawed. We have clarified the logic of our arguments in the text. As mentioned above, it is unreasonable to draw conclusions beyond the information available in the data. Therefore, we reconsidered the atmospheric system responsible for aeolian dust dynamics in our study area, and then rewrote and rearranged the paragraphs.

As explained above, the Siberian high-pressure systems exerted a significant influence on wind dynamics responsible for dust transport and the accumulation of loess deposits during cold phases in NLK, and the mid-latitude Westerlies controlled the patterns of moisture variations in Arid Central Asia (ACA), based on modern and Holocene climate data and comparison of the EM1 proportions and mean grain size (MGS) data from the Jingyuan section in northwestern CLP. A strengthened Siberian High would push the mid-latitude Westerlies pathways further to the south, which resulted in comparably drier conditions in the northern Central Asia regions (e.g. Tianshan Mountains) but wetter conditions in south-western Central Asia (Pamir) (Lei et al., 2014;Wolff et al., 2017). Intensity and geographical position of the Siberian High can strongly control precipitation and atmospheric circulation patterns (meridional or zonal) at mid-latitudes of Asia (Panagiotopoulos et al., 2005). Therefore, the coupling of the Siberian High with the mid-latitude Westerlies system likely contributed significantly to the climate variability in the study area, which may interpret the seesaw relationship during MIS3 shown in Fig. 7 of manuscript.

***Replies to the comments of editor***

**C&S**: Please revise your manuscript by incorporating the changes that you have made in response to the referees' comments. My concern with this manuscript is that the discussions and conclusions are based on one loess section. The title with the words such as environmental dynamics doesn't really reflect the level of science that you try to convey in the manuscript. Please re-consider the title.

**A&R**: We have rechecked and further considered the correlation of EM1 proportions and GISP $\delta^{18}O$ from the Greenland ice cores. Although it may not be possible to reliably match fluctuations in loess records to millennial climatic events due to the limitations in dating techniques in loess research, our grain-size proxy data can still correlate with abrupt events, such as Heinrich events (H1 to H6) identified from the North Atlantic records (Fig. 7 in the revised manuscript). However, EM1 proportions fluctuate weaker in H2 and H5 events, which we attribute to availabilities of source sediments, as mentioned above. These millennial-scale events were also found in Xiaoerbulake section, Talede section and Zhaosu section from the Ili Basin (Li et al., 2016a;Li et al., 2011a;Zhang et al., 2015). However, in our opinion, the Siberian high-pressure systems predominate in the Ili Basin during cold phases, which leads to dust transport and increased loess accumulation at NLK and is responsible for those North Atlantic millennial scale abrupt climate events. Therefore, our data support the Siberian High can also transport the climatic signals in the North Atlantic to the East Asia, via the ice sheets in high northern latitudes. Moreover, lack of good correlation between EM1 proportions and GISP $\delta^{18}O$ values during relatively mild interstadial periods (Dansgaard-Oeschger cycles) when the mid-latitude westerlies shift northwards, implies the minor direct influences of the mid-latitude westerlies on the loess accumulation in NLK, which is not in agreement with the previous studies.

In addition, some of the peaks in EM1 curve correspond to valleys in GISP $\delta^{18}O$ curve (black arrows in Fig. 7 in the manuscript) except Heinrich events, yet many do not (pink dashed lines in Fig. 7 in the manuscript). The same case also occurs in the Western CLP (Chen et al., 1997), that is, all of the Heinrich events occurred during periods of strong winter monsoon in China, but not all of the periods of strong winter monsoon in China correlate with Heinrich events in the North Atlantic. The differences may be because the loess records in our study area represent a response not only to global signals but also local signals such as local atmospheric circulation and topography.

We have rewritten the title, “Aeolian dust dispersal patterns since the last glacial period in eastern Central Asia: Insights from a loess-paleosol sequence in the Ili Basin, northwest China”. Thank you.

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# A list of all relevant changes made in the manuscript

Line numbers in following parts refer to those in the *Marked-up Manuscript*.

***Figure***

1. We have improved the quality of Figure 1, changed front size and enlarged this figure.
2. We added the mean grain size record of the Jingyuan loess section and U-ratios (15.6–63.4 μm/5.61–15.6 μm) of the SE Kazakhstan loess to Figure 7, in an effort to support our argument that the Siberian high-pressure system exerts a significant influence on wind dynamics and therefore loess deposition processes at NLK.

***Running text***

1. Line 1-4: We have rewritten the title.
2. Line 27: We substituted “records” with “archives”.
3. Line 29-37: We have simplified and clarified our expression regarding MS.
4. Line 39-40: “are inferred to” was added into this sentence and “the” was deleted.
5. Line 41-42: We substituted “the” with “a”, and “processes” with “conditions”.
6. Line 43-60: We have rewritten this part according to the revised section 5.3 to make the abstract more logical, and have clarified that the Siberian high-pressure system was most likely the strongest influence on wind dynamics and thus the loess deposition in NLK.
7. Line 67-69: The range of arid Central Asia is defined.
8. Line 75-76: We substituted “Central Asian region” with “ACA”.
9. Line 77-78: We deleted the repeative sentence.
10. Line 79-82: We added names of the mountain ranges where Central Asia piedmont loess is distributed.
11. Line 85-87: We have simplified our expression.
12. Line 89: We substituted “temperature” with “millennial-scale climatic”.
13. Line 92-100: We have simplified our expression.
14. Line 101-110: We have simplified and clarified our expression and the objective of this paper.
15. Line 113-117: We have simplified these sentences.
16. Line 125-126: We added the modern meteorological data on MAP and MAT at NLK.
17. Line 127-129 and 135-137: We changed the position of this sentence.
18. Line 146: We deleted the sentence “confirmed by our subsequent grain size and magnetic susceptibility (MS) results”.
19. Line 149-155: We have simplified and clarified these sentences.
20. Line 165: We have deleted “established by”, and rewritten the words, like this “(BEMMA; Yu et al. (2016))”.
21. Line 168-172: We have clarified the measurement processes of quartz grain size.
22. Line 177: We added the word “precisely”.
23. Line 219 and 232: We have changed the position of Figure 4.
24. Line 236-237: We have changed the subtitle.
25. Line 238-265: We have simplfied these two paragraphs and cut out everything that’s not necessary to make our meanings clearer.

26. Line 266-286: We have polished the language of these three paragraphs.
27. Line 291-293: We have substituted “typically conducive to” with “associated with”, and deleted “including high precipitation and rising groundwater levels”.
28. Line 297: We deleted the sentence “and yet very weak pedogenesis was reflected by $\chi_{fd}$”.
29. Line 300-301: We have deleted the first sentence of this paragraph.
30. Line 308-322: We have rewritten this paragraph and added a literature in order to state that the “wind theory” can be used to decipher the MS variations of NLK loess.
31. Line 324-357: We have added a comprehensive and streamlined review on existing literature dealing with interpretation of loess particle size, including the two dominant approaches to unmixing grain size spectra and successful applications of sediment groups according to Vandenberghe (2013) to interpret the multiple sources for loess sediments.
32. Line 368: We substituted “stocks” with “supplies”.
33. Line 370: We wrote “aeolian transport” to “entrainment”.
34. Line 381: We substituted “therefore” with “rather”.
35. Line 383: We clarified this sentence.
36. Line 388-390: We splited original sentence into two sentences.
37. Line 195: “fallout” was added.
38. Line 401-402: We splited original sentence into two sentences.
39. Line 413: We have clarified the statement of Zhang et al. (1999)
40. Line 423-425: We added a line of evidence for supporting that finer single particles could settle down during low velocity wind condition.
41. Line 427-440: We have simplified and clarified these sentences.
42. Line 467-474: We have clarified these sentences.
43. Line 489-493: We have revised the caption of Figure 7, and added two curves (MGS and U-rato) and deleted the summer insolation curve.
44. Line 497: We have deleted the sentence “Based on the independent chronology sequences”.
45. Line 500-504: We have dded two curves (MGS and U-rato)and deleted the summer insolation curve.
46. Line 505-520: We clarified this paragraph.
47. Line 524-690: We have reconsidered and rewritten this part. We now list the arguments for the significant influence of the Siberian high-pressure system on wind dynamics and thus loess deposition in the eastern Ili Basin, and acknowledge the role of the mid-latitude Westerlies in controlling broad-scale patterns of moisture variation across ACA. The coupling of the Siberian High with the mid-latitude Westerlies system most likely had the strongest influence on climate variability at NLK in the eastern Ili Basin. Moreover, our data support the hypothesis that the Siberian High forms a teleconnection between the climatic systems of the North Atlantic and East Asia, via the ice sheets in high northern latitudes, with the exception of the mid-latitude westerlies. We have made the section 5.3 clearer and more logical.
48. Line 692-697: We have simplified and clarified our expression about MS.
49. Line 698: We have deleted the sentence “With the unmixing of grain size dsitributions”.
50. Line 706-720: We have revised the last part of conclusion according to the revised section 5.3.

# ~~Environmental dynamics~~Aeolian dust patterns since the last glacial period in ~~arid~~ eastern Central Asia: ~~evidence~~ Insights from ~~grain size distribution and magnetic properties of~~ a loess~~-~~paleosol sequence ~~from the Ili Valley~~in the Ili Basin~~, western China~~

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**Abstract**

The extensive loess deposits of the Eurasian mid-latitudes provide important terrestrial archives ~~records~~ of Quaternary climatic change. As yet, however, loess records in Central Asia are poorly understood. Here we investigate the grain size and magnetic characteristics of loess from the Nilka (NLK) section in the Ili Basin of eastern Central Asia. ~~Magnetic parameters indicate very weak pedogenesis compared with loess from other regions in Eurasia.~~ Weak pedogenesis suggested by frequency-dependent magnetic susceptibility ($\chi_{fd}$%) and magnetic susceptibility (MS) peaks ~~The higher $\chi_{lf}$ values occur~~ in primary loess suggest that MS is more strongly influenced by allogenetic magnetic minerals than pedogenesis, and may therefore be used to indicate wind strength. This is supported by the close correlation between variations in MS and proportions of the sand-sized fraction.~~, rather than in weak paleosols, and the variations in magnetic susceptibility (MS) value correlate closely with the proportions of the sand fraction. We attribute this result to high wind strength at the time of loess deposition.~~ To further explore the temporal variability in dust transport patterns~~ further~~, we identified three grain size end members (EM1, mode size 47.5 μm; EM2, 33.6 μm; EM3, 18.9 μm) which represent distinct aerodynamic environments. EM1 and EM2 are inferred to represent ~~the~~ grain-size fractions transported from proximal sources in short-term, near-surface suspension during dust outbreaks. EM3 appears to represent ~~the~~ a continuous background dust fraction under non-dust storm ~~processes~~conditions. Of the three end members, EM1 is most likely the most sensitive recorder of wind strength. We compare our EM1 proportions and mean grain size from NLK with the Jingyuan section in the Chinese loess plateau, and assess these in the context of modern and Holocene climate data, and suggest that the Siberian high-pressure system is the dominant influence on wind dynamics and thus loess deposition in the eastern Ili Basin. Six millennial-scale cooling (Heinrich) events can be identified in the NLK loess records. Our grain-size data support the hypothesis that the Siberian High acts as teleconnection between the climatic systems of the North Atlantic and East Asia in the high northern latitudes, but not for the mid-latitude westerlies. ~~A lack of correlation between EM1 proportions and GISP $\delta^{18}$O values at the millennial scale, combined with modern weather data, suggests that Arctic polar front predominates in the Ili Basin and the Kyrgyz Tian Shan piedmont during cold phases, which leads to the dust transport and accumulation of loess deposits, while the shift of mid-latitude westerlies towards the south and north controls the patterns of precipitation/moisture variations in this region. Comparison of EM1 proportions with Northern Hemisphere summer insolation clearly illustrate local insolation-based control on wind dynamics in the region, and humdity can also influence grain size of loess over MIS3 in particular. Although, the polar front dominated wind dynamics for loess deposition in the region, the Central Asian high mountains obstructed its migration further south. Our results may also support the significance of the mid-latitude westerlies in transmitting North Atlantic climate signals to East Asia.~~

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Key words: Last glacial, Ili Basin, Central Asia, loess, magnetic susceptibility, grain size, paleoclimate

## 1 Introduction

Central Eurasia experiences extremely continental climatic conditions in large part due to its position far from the oceans. Arid Central Asia (ACA), the mid-latitude region spanning the Caspian Sea across to the eastern Tien Shan mountains, is therefore a sensitive recorder of past climate change due to its location in the transitional region ~~zone~~ between the Asian monsoon (Dettman et al., 2001;Cheng et al., 2012), mid-latitude westerlies (Vandenberghe et al., 2006) and North Asian polar front (Machalett et al., 2008). The relative influence and intensity of these major climate subsystems have varied across the latitudinal and longitudinal range of Central Asia through time. Thus identification of the predominant climate regimes in a certain region is a crucial precondition for tracing paleoclimatic evolution.

One of the most promising potential palaeoenvironmental archives in the ~~Central Asian~~ACA ~~region~~ is its widespread, thick loess deposits. Loess is one of the most important archives of Quaternary climate change (Maher, 2016;Muhs, 2013). ~~The semi-arid zone of Eurasia, between 45° and 30° N, hosts some of the thickest and most extensive loess deposits in the world.~~ In Central Asia, the loess deposits ~~cover~~ drape the piedmont slopes of the major mountains ranges - the Tian Shan ~~mountains~~, Alai, Altai and Pamirs - from Xinjiang province of China ~~and~~ through Kazakhstan, ~~to~~ Kyrgyzstan and Uzbekistan, into Tajikistan. While ~~loess in Central Asia has increasingly formed the focus of~~ recent years have witnessed increasing loess-based datasets ~~research~~ in the region (Dodonov et al., 2006;Feng et al., 2011;Li et al., 2016c;Li et al., 2016b;Machalett et al., 2006;Smalley et al., 2006;Song et al., 2014;Song et al., 2015;Song et al., 2012;Yang et al., 2006;Youn et al., 2014;Fitzsimmons et al., 2016), ~~as yet~~ the forcing mechanisms and the climatic conditions responsible for loess-paleosol sequences formation are as yet ~~ambiguous, and the paleoclimatic evolution recorded by these loess deposits in this region is~~ not systematically understood (Li et al., 2016a;Fitzsimmons et al., 2016;Machalett et al., 2008).

Evidence for ~~temperature~~ millennial-scale climatic oscillations associated with the Greenland (*Dansgarrd/Oeschger (D-O) events*) (Dansgaard et al., 1993) and cool phases associated with iceberg calving into the North Atlantic (*Heinrich (H) events*) (Bond et al., 1992) have been found in the form of ~~loess deposits based on the high-resolution~~ grain-size variations ~~ether~~ in loess deposits in Chinese Loess Plateau (CLP) ~~loess~~ (Sun et al., 2012;Porter and An, 1995;Chen et al., 1997b) ~~or in~~and European ~~loess~~ (Antoine et al., 2009;Rousseau et al., 2007;Zeeden et al., 2016). ~~Climatic teleconnections, especially between the North Atlantic and East Asian Monsoon regions, are likely to have been recorded within the~~ Data for Central Asian loess do not as yet exist~~. As yet, however, the region so far largely lacks~~ at this resolution, despite its strategic location as a likely environmental bridge between the North Atlantic and East Asian Monsoon climatic regions.~~data by which the role and contribution of the central parts of the Eurasian continent, as an environmental bridge, can be elucidated.~~

The Ili Basin of Central Asia ~~represents a region of~~ hosts thick loess deposits in the strategic central eastern part of ACA (Song et al., 2014) ~~with high potential for investigating palaeoenvironmental change for the region~~. The ~~situation of the~~ basin ~~,~~ is surrounded to the south and north by the Tian Shan mountain range, ~~and~~ widens~~ing~~ to the west and drains into endorheic Lake Balkhash (Fig. 1), and provides a conducive situation for loess accumulation. ~~which has resulted in the widespread and thick loess deposits in this basin.~~ In this paper we present new data on the physical properties of a 20.4 m thick loess deposit at Nilka (NLK) in the eastern Ili Basin~~,~~. ~~focusing on~~We investigate variations in grain size distributions and magnetic properties in order to investigate likely links with environmental dynamics ~~the enhancement mechanisms of magnetic susceptibility in NLK loess and elucidate environmental dynamics based on grain size data~~.

## 2 Physical geography

The Ili Basin (80° ~ 85° E and 42° 30′ ~ 44° 30′ N) straddles southeast Kazakhstan and northwest China. It is an intermontane basin opening westward towards the Ili drains into Lake Balkhash~~the semi-arid Kazakhstan Gobi Desert~~ which ~~forms~~ is in the semi-arid ~~the~~ transitional region between the steppe and full deserts of Central Asia. The Northern and Southern Tian Shan form the northern and southern ~~boundaries to~~margins of the basin (Fig. 1a).~~ The Ili River drains northwestward into terminal Lake Balkhash.~~

This region has a semi-arid, continental climate, with a strong precipitation gradient dependent on altitude. The altitude of the basin floor is 500 ~ 780 m; the northern ~~Tien~~ Tian Shan Range reaches altitudes of > 4000 m a.s.l. and the southern ~~Tien~~ Tian Shan mountains range between 3000 ~7000 m a.s.l. towards the catchment divide. ~~The m~~Mean annual precipitation (MAP) ranges between 200 ~~mm and~~ - 500 mm on the plains, and mean annual temperature (MAT) ranges from 2.6°C ~~to~~ - 10.4°C (Li, 1991;Ye, 1999). The surface vegetation in this region is dominated by *Desert Steppe* and *Steppe* and the zonal soils comprise *Sierozem*, *Castonozem* and *Chernozem*.

Modern meteorological data (2009 – 2013) show a MAP of 354 mm and a MAT of 7.3°C in Nilka site (data from the China Meteorological Data Network: http://data.cma.cn/).

~~The Nilka (NLK) section (83.25°E, 43.76°N, 1253 m a.s.l) is situated on the second terrace of the right bank of the Kashi River, a tributary of the Ili River. The site is located in the eastern Ili Basin of far western China, adjoining the Northern Tian Shan to the north (Fig. 1b).~~

Fig. 1 The location of study area and the photo of Nilka (NLK) section.

## 3 Materials and methods

### 3.1 Section and sampling

The Nilka (NLK) section (83.25°E, 43.76°N, 1253 m a.s.l) is situated on the second terrace of the right bank of the Kashi River, a tributary of the Ili River. The site is located in the eastern Ili Basin of far western China, adjoining the Northern Tian Shan to the north (Fig. 1b).

The~~ NLK loess~~ section has a thickness of 20.4 m and overlies fluvial sands and gravels (Fig.1c). The profile has been exposed recently by local residents for making bricks, and recently formed the focus of a geochronological study comparing luminescence with radiocarbon methods (Song et al., 2015). According to the dating results ~~of~~, the NLK loess started to accumulate since ~ 70 ka~~ B.P.~~. Stratigraphically and geochronologically, this is equivalent to the L1 loess unit (known as Malan loess) and S0 paleosol unit (also known as Holocene Heilu soil) in the ~~Chinese Loess Plateau~~CLP(Liu, 1985a)~~, 2300 km to the east~~. Although largely homogeneous in appearance, two weak paleosols (at 5.04 − 7 m and 15.7 − 18 m depths) were identified in the section by field observations~~ and confirmed by our subsequent grain-size and magnetic susceptibility (MS) results~~. We therefore divided the NLK stratigraphy into S0, L1L1, L1S1, L1L2, L1S2 and L1L3 units (Fig. 1c).

~~Following~~ After cleaning ~~back of~~ the NLK section to remove dry, weathered sediment, samples were collected at intervals of 2 cm. A total of 1026 bulk samples were prepared for measurements of physical characteristics. Because the optically stimulated luminescence (OSL) dating is more reliable for constructing a loess chronology than bulk sediment AMS $^{14}$C dates (Song et al., 2015), t~~T~~his study uses the previously published ~~more reliable optically stimulated luminescence (~~OSL) dating results as basis for ~~the~~ our age model~~ and assessment of the evolution of loess physical~~

~~characteristics~~.

### 3.2 Grain-size analyses

Prior to grain size measurements, 0.5 g of dry bulk sample was pretreated by removal of organic matter and carbonate using $H_2O_2$ and HCl, respectively (Lu and An, 1997). Samples were then dispersed for 5 min by ultrasonification with 10 ml 10% $(NaPO_3)_6$ solution. Grain size distribution was analysed using a Malvern 2000 laser instrument at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences. Particle size distribution was calculated for 100 grain size classes within a measuring range of 0.02−2000 μm. Replicate analyses indicated an analytical error of < 2% for the mean grain size.

End-member unmixing of loess grain-size distributions is based on the hierarchical Bayesian model for end-member modeling analysis (BEMMA~~;) established by~~ Yu et al. (2016)). Grain-size parameters were calculated from the analytical data with GRADISTAT (Version 4.0; Blott (2000)).

2 samples (NLK1106 at 11.06 m and NLK1840 at 17.8 m) were also selected for the extraction and measurement of mineral-specific ~~of~~ quartz grain size~~s~~ according to published methods of Sun et al. (2000a). The isolated quartz grain samples (Fig. S1) were then ~~placed into~~ analyzed by the Malvern 2000 laser instrument ~~for mineral-specific grain size measurements~~ so that comparisons of quartz grain and bulk samples could be performed to illustrate the weathering degree of NLK loess ~~visually~~.

### 3.3 Magnetic susceptibility measurements

Magnetic susceptibility was measured with a Bartington MS2 meter at the State Key laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences. Samples were oven-dried at 40°C for 24 hours. Subsamples of 10 g from each sample were then precisely weighed for magnetic measurements. Low- (0.47 kHz) and high- (4.7 kHz) frequency magnetic susceptibility ($\chi_{lf}$ and $\chi_{hf}$, respectively) were measured. The absolute frequency-dependent magnetic susceptibility was calculated as $\chi fd = \chi_{lf} - \chi_{hf}$. Frequency-dependent magnetic susceptibility was defined and calculated as $\chi_{fd}\ \% = [(\chi_{lf} - \chi_{hf})/\ \chi_{lf}] \times 100\%$.

## 4 Results

### 4.1 Magnetic susceptibility variations

Both magnetic susceptibility (MS) data and stratigraphy show a close correspondence throughout the NLK section. We observe higher MS values within primary loess and lower values within paleosols. The exception to this trend is the modern (S0) soil ~~in~~ which yields high MS values ~~are presented~~ (Fig. 2).

Fig. 2 Lithology and magnetic susceptibility characteristics ($\chi_{lf}$, $\chi_{fd}$ and $\chi_{fd}$%) of the NLK section.

The ~~low-frequency magnetic susceptibility ($\chi_{lf}$)~~ values of the S0 unit are higher than for the L1 unit, with an average of 98.13 × $10^{-8}m^3kg^{-1}$. The $\chi_{lf}$ values of the L1L1 unit vary from 56.5 − 103.9 × $10^{-8}m^3kg^{-1}$, ~~with a~~ decreasing ~~trend~~ down-profile. The $\chi_{lf}$ value abruptly decreases at c. 5 m, with generally lower values in the L1S1 unit, averaging 62.58 × $10^{-8}m^3kg^{-1}$. $\chi_{lf}$ in the L1L2 unit gradually increases down profile, with significant fluctuations in the lower part; $\chi_{lf}$ values vary from 67 − 102.55 × $10^{-8}m^3kg^{-1}$. Lower $\chi_{lf}$ values are observed in L1S1 unit with an average value of 57.99 × $10^{-8}m^3kg^{-1}$. In the L1L3 unit, the $\chi_{lf}$ values vary with greater amplitude around an average value of 68.74 × $10^{-8}m^3kg^{-1}$.

Absolute frequency-dependent magnetic susceptibility ($\chi_{fd}$) values likewise vary with stratigraphy. The S0 unit yields the highest $\chi_{fd}$ value. The L1 unit is characterized by relatively consistent and lower $\chi_{fd}$ values. Frequency-dependent magnetic susceptibility ($\chi_{fd}$%) yields the same trend as $\chi_{fd}$, although $\chi_{fd}$% values clearly increase in the central part of L1S2.

### 4.2 Mixing model of loess grain-size distributions

The mean grain-size distribution, and variation range of volume frequencies for each grain-size class in the dataset, are presented in Fig. 3a. The overall grain-size frequency curve shows a unimodal pattern, if slightly skewed towards the coarser side, with the primary mode ranging from 11.9 ~~µm to~~ 47.5 µm. An additional small grain size peak occurs at c. 0.4 – 2 µm. Three unmixed end members were identified (Fig. S2), yielding fine-skewed grain-size distributions with clearly defined modes of 47.5 µm (EM1), 33.6 µm (EM2) and 18.9 µm (EM3) (Fig. 3b).

Fig. 3 End-member modelling results of the grain-size dataset of the NLK section. (a) Mean size distribution and range of volume frequency for each size class. (b) Modelled end-members according to the three-end-member model (modal size: ~ 47.5 µm, ~ 33.6 µm and ~ 18.9 µm). Size limits of clay, silt and sand fractions determined by laser particle sizer are differ from those derived by the pipette method. The upper limits of grain-size classes used here are at 4.6/5.5 µm for clay, 26 µm for fine silt, and 52 µm for coarse silt, as previously published by Konert and Vandenberghe (1997). Sand is designated for particle sizes > 52 µm. Therefore, EM1 and EM2 correspond to coarse silt and EM3 to fine silt.

~~Fig. 4 Proportional contributions of the three end-members in the NLK section.~~

The proportional distribution of the end members down the section is shown in Fig. 4. In the primary loess units (L1L1, L1L2 and L1L3), the deposits are dominated by the coarser silt EM1 and EM2, while higher proportions of fine silt EM3 are ~~preferentially~~ observed within the soil horizons (S0, L1S1 and L1S2). EM1 displays high frequency, large amplitude fluctuations down the profile, varying between 0.09 – 0.72, and clearly dominates the primary loess units and occurs in low proportions in the soil units (Fig. 4). EM2 shows a similar trend to EM1, but with less variability down profile. Proportions of EM2 range between 0.11 − 0.66 with minimal fluctuations within individual units, and proportions decrease significantly in the soil units S0 and L1S2. Proportions of EM3 remain consistently low within the primary loess units, and increase to 0.46 and 0.8 within the soil horizons S0 and L1S2 respectively.

Fig. 4 Proportional contributions of the three end-members in the NLK section.

## 5 Discussion

### 5.1 Impacts of wind strength on magnetic susceptibility variations~~Likely mechanisms for the enhancement of magnetic susceptibility in Ili Basin loess~~

Magnetic susceptibility (MS) in loess is predominantly determined by ~~due to~~ the concentration of iron-bearing magnetic minerals within the sediment (Liu et al., 1999;Liu et al., 1994;Song et al., 2010). ~~At the broadest level~~Generally, this varies between primary loess. ~~and s~~Soil horizons, with soils generally ~~experiencing~~ experience an enrichment ~~of~~ in magnetic minerals (higher MS), ~~and corresponding higher MS values, than~~ compared with primary loess ~~deposits~~ (Zhou et al.,

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1990;Maher and Thompson, 1992;Heller and Evans, 1995;Heller and Liu, 1984;Ding et al., 2002;Buggle et al., 2009).~~ The formation *in situ* of < 100 nm magnetite or maghemite grains during pedogenesis is the most widely accepted interpretation for the mechanisms of loess MS enhancement . Increased precipitation is conducive to chemical weathering and biological processes during pedogenesis. Song et al. (2010) further argued that strong pedogenesis under warm, humid climatic conditions produces new magnetic minerals.~~

The contrast between high and low MS in paleosols and primary loess, respectively, ~~has~~ typically forms~~ed~~ the basis for the stratigraphic differentiation of loess deposits. ~~This principle has provided the foundation for large-scale correlations between loess deposits and with global climatic oscillations , initially in the Chinese Loess Plateau deposits and increasingly worldwide.~~

The main MS variations in the NLK loess sequence, with the exception of the S0 unit, however, do not occur directly in association with pedogenesis (Fig. 2). At NLK, lower MS values are found in the paleosols and higher MS in loess units. A similar case also occurs in the L1 loess layers at other sites in the Ili Valley, such as ~~in~~ the TLD, ZKT and AXK sections~~, also in the Ili valley~~ (Fig. 1) (Jia et al., 2010;Jia et al., 2012;Song et al., 2010).~~ The lack of a straightforward correlation between MS, loess and paleosols indicates that an alternative explanation for this variability must be sought. Proposed mechanisms of variations in loess magnetic susceptibility include, in addition to pedogenesis , the dilution of relatively coarse silt with a low susceptibility , sediment compression and carbonate leaching , and decomposition of plant residues .~~

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~~Since alternative mechanisms may have played a role in the magnetization of the Ili Basin loess deposits, we investigated different aspects of environmental magnetic properties in order to investigate to what degree pedogenesis or the alternative mechanisms played the more critical role in this region.~~

~~Absolute frequency-dependent susceptibility (~~$\chi_{fd}$~~)~~ ~~determines~~ indicates the concentration of magnetic particles within a small grain size range across the superparamagnetic (SP)/stable single domain (SSD) boundary (Liu et al., 2012) (magnetite, <~100 nm; maghemite, <~20 μm). Particles with this grain size are considered to form in situ within soils during pedogenesis (Maher and Taylor, 1988;Zhou et al., 1990)~~, and~~. ~~therefore~~ Therefore, $\chi_{fd}$ can serve as a direct proxy for pedogenesis (Heller et al., 1993;Maher and Thompson, 1995;Liu et al., 2007;Buggle et al., 2014). In the NLK section, $\chi_{fd}$ yields consistently low values throughout the sequence and indicates no clear enrichment ~~strong pedogenesis~~ even in the ~~weakly developed~~ paleosol layers ~~(~~L1S1 and L1S2~~)~~. Comparison between $\chi_{lf}$ vs. $\chi_{fd}$ down profile shows no correlation between MS and SP particles (Fig, S3c). These results suggest that SP particles played only a minor role in MS enhancement in the NLK loess.

~~Frequency-dependent magnetic susceptibility (~~$\chi_{fd}$%~~)~~ is used as a proxy to determine the contribution of SP particles to MS (Zhou et al., 1990;Liu et al., 1992). At NLK section, however, we also observe consistently low $\chi_{fd}$% values in both loess and paleosol layers, with a slight increase only in the L1S1 paleosol. This observation reinforces our interpretation that the content of SP particles is very low, and consequently that their contribution to MS can be ignored.

The low proportions of SP particles in the NLK loess imply that the pseudo-single-domain (PSD) and multi-domain (MD) magnetic grains, rather than SP grains forming in situ, are more influential for the ~~make the more important contribution to~~ magnetic enhancement ~~of NLK loess~~at this site. Since PSD and MD magnetic minerals are difficult to produce during pedogenesis (Song et al., 2010), such minerals are more likely to be detrital in nature, deriving from the original protolith.

Fig. 5 Comparison of different grain size fractions of NLK loess with $\chi_{lf}$ (limits of grain-size classes after Konert and Vandenberghe (1997) ).

In some cases, ~~the~~ moist conditions ~~typically conducive to~~ associated with pedogenesis~~, including high precipitation and rising groundwater levels,~~ may result in the weathering~~,~~ and ~~destruction and~~ dissolution of the magnetic minerals maghemite and magnetite (Nawrocki et al., 1996;Maher, 1998;Grimley and Arruda, 2007). In such cases, a negative relationship between magnetic susceptibility and pedogenesis can develop, in contrast to the classical situation whereby $\chi_{fd}$ is enhanced. At NLK section, however, we observe no textures caused by groundwater fluctuations. ~~, and yet very weak pedogenesis was reflected by~~ ~~$\chi_{fd}$.~~ We therefore exclude groundwater fluctuations and high levels of precipitation as a factor in our MS characteristics at NLK section.

~~Increased concentrations of coarser-grained detrital magnetic minerals, resulting from periods of increased wind strength, may enhance overall MS values.~~ In the wind velocity/vigor model (also known as the Alaskan or Siberian model), wind strength affects magnetic susceptibility values of loess through the physical sorting of magnetic grains (Beget and Hawkins, 1989). The influence of this process on MS values in loess can be assessed by investigating the correlation between MS and coarser (silt or sand) and finer clay percentages (Fig. S3). At NLK, low MS values in the S0 soil between 0 – 0.5 m correlate positively with clay percentage variations (Fig. S3a), while higher MS values at depths greater than > 0.5 m correlate closely with increased sand concentrations (Fig. S3b). We therefore propose that MS enhancement at NLK is ~~primarily~~ likely driven by wind strength. ~~increased concentrations of sand-sized detrital magnetic minerals, which increase during periods of stronger winds. The dilution effect of coarse particles with low susceptibility was excluded.~~

~~In the case of NLK, the reduced color contrast (Fig. 1) between loess and paleosol layers implies moderate climate fluctuations between loess deposition and pedogenesis due to generally more arid conditions than typically experienced in loess regions.~~ Under this scenario, weak pedogenesis ~~This~~ prevented~~s~~ the efficient production of SP grains (Fig. 2), and allogenetic magnetic minerals associated with dust transportation made a greater contribution to the MS. Wind strength can therefore be interpreted ~~regarded~~ as ~~a~~ the main ~~factor for~~influence on MS variations ~~since last glacial~~At NLK. The enhancement of magnetic susceptibility in NLK loess most likely falls into region A in Fig. 9 of Liu et al. (2013). Region A represents the area where the climate is arid and pedogenesis is weak and, dominated by physical weathering (Liu et al., 2013). Therefore, we can use the “wind theory” to decipher the MS variations of NLK loess. Weak pedogenesis enables preservation of primary atmospheric dust contribution to NLK.~~And in turn, MS may be able to indicate stronger wind during dust storms.~~

**5.2 Genetic interpretations of end members in loess grain size**

~~In order to understand the atmospheric dynamic pattern during loess deposition further, we conducted unmixing of grain-size distributions.~~

~~Recent years have seen increasing statistical analysis of loess grain-size to identify subpopulations within bulk samples . From these statistical datasets, the different end members can be interpreted to infer distinct atmospheric transport mechanisms, modes and travel distances . In some cases, the end-member approach has been used to identify variation in geological context, or source area . We investigated the utility of this approach to the Ili Basin loess at NLK by unmixing~~

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~~grain-size distributions with BEMMA . As shown in Fig. S2, we generated a mixing model consisting of three end members.~~

Grain-size analysis was conducted in order to understand wind dynamics (strength and direction) during loess deposition (Liu, 1985b;Lu and An, 1998;Sun et al., 2010). Grain-size analysis provides information on sediment depositional mechanisms as well as an insight into spatio-temporal changes in deposition, provided factors such as vegetation, pedogenesis, grain size of source sediments, and distance from the deposition area to source area are taken into account (Qin et al., 2005;DiPietro et al., 2017;Obreht et al., 2015;Terhorst et al., 2012;Ding et al., 2005;Ding et al., 1999;Yang and Ding, 2008).

Statistical analysis of loess grain-size offers new opportunities for understanding paleoclimate variations. Studies increasingly use grain size partitioning to identify subpopulations within bulk samples. There are two dominant approaches to unmixing grain size spectra: parametric decomposition (e.g. Sun et al., 2002) and non-parametric decomposition (e.g. Prins and Vriend, 2007;Weltje, 1997; Weltje and Prins, 2007) . Based on the statistical datasets generated, the different end members can be interpreted to infer distinct atmospheric transport mechanisms, modes and travel distances (Ujvari et al., 2016). In some cases, the end-member approach has been used to identify variation in the geological context or source area (Prins et al., 2007). We investigated the applicability of this approach to the Ili Basin loess at NLK by unmixing grain-size distributions with BEMMA (Yu et al., 2016), generating a mixing model consisting of three end members (Fig. S2).

Relying largely on samples from Eurasian loess belt extending from the Russian Plain north of the Caspian Sea eastwards to the Tibetan Plateau and CLP, Vandenberghe (2013) applied the visual inspection of grain-size distribution curves and EMMA end-member analysis to define the characteristic grain-size distribution of primary loess deposits and interpret the likely conditions of transport and deposition. Using the sediment groups identified in Vandenberghe (2013), some studies interpreted multiple sources for loess sediments (Yang et al., 2016;Nottebaum et al., 2015;Nottebaum et al., 2014). In this study, we apply the end-member analysis of the NLK loess to the sediment groups of Vandenberghe (2013) in an effort to reconstruct dominant aeolian processes.

Fine sand (‘*sediment type 1.a*’ in Vandenberghe (2013)) is a typical component of loess deposits near to or overlying river terraces. Although the NLK section lies on the second terrace of the Kashi River and therefore closer to a potential source of coarser grained material, the fine-sand end member is completely absent. Modal grain sizes in this range (c. 75 um) are common in loess along the Huang Shui and Yellow Rivers in China (Vriend and Prins, 2005;Vandenberghe et al., 2006;Prins et al., 2009), the Danube and Tisza rivers in Serbia (Bokhorst et al., 2011), and the Mississippi valley in the USA (Jacobs et al., 2011). This fraction is generally interpreted to originate from proximal sources, and the grain size of the available source material plays a more important role in determining the grain-size characteristics of this fraction than wind energy (Vandenberghe, 2013). The lack of fine sand at NLK, despite its proximity to the Kashi River, may be attributed to 1) its location in the upper reaches of the river (Fig. 1b), in a region which lacks available ~~stocks~~ supplies of fine sand, 2) the V-shaped nature of the channel which is not conducive to ~~aeolian transport~~entrainment of bank deposits, and 3) the relatively high altitude of NLK within the basin which inhibits transport and deposition of coarser sediment grains (Vandenberghe, 2013).

The three members (Fig. 3b) identified at NLK correspond to coarse silt (EM1 and EM2) and fine silt (EM3). Each likely represent different kinds of depositional processes which operated throughout the accumulation of the deposit at NLK. Here we focus on the implications of these three end members for understanding past environmental conditions responsible for loess-paleosol sequences formation.

EM1 has a modal grain size of 47.5 µm (Fig. 3b), which approximately corresponds to the '*subgroup 1.b.1*' of Vandenberghe (2013). The mode is similar to end members identified in loess from the ~~Chinese Loess Plateau (~~CLP~~)~~ and the north-eastern Tibetan Plateau (NE-TP) (EM-2: 44 µm) (Vriend et al., 2011). The size of this component is unlikely to be due to longer distance transport. ~~Therefore~~ Rather, it is inferred ~~that EM1 is~~to derive~~d~~ from shorter distance transport of suspended load (Vriend et al., 2011;Vandenberghe et al., 2006). Coarser particles (>20 µm) ~~with grain-size >20 um~~ rarely reach suspension above the near surface level (0 − 200 m above the ground). When entrained by wind, they do not remain in suspension for long enough to travel long distances (Tsoar and Pye, 1987;Pye, 1987). Since the average grain-size of EM1 is 26.74 µm (calculated after Folk and Ward (1957)), we infer that this fraction was transported mainly ~~in~~ during short-term suspension episodes at lower elevations by surface winds, and deposited short distances downwind of the source. These short-term suspension episodes may correspond to spring-summer dust storms.~~,~~ Our interpretation is supported ~~as demonstrated~~ by present-day dust measurements on the CLP which ~~detected~~ identify a similar modal grain-size during ~~these~~ such events (Sun et al 2003).

EM2 represents a mode at 33.6 µm (Fig. 3b). It lies towards the finer end of the range of '*subgroup 1.b.2*' (Vandenberghe, 2013). Comparable loess of the same grain size has been identified in loess from the northern Qilian Shan/Hexi Corridor (EM2: 33 µm) in northern China, which was also interpreted as depositing from short-term suspension (Nottebaum et al., 2015). Loess of this grain size has been attributed to dust fallout (Pye, 1995;Muhs and Bettis, 2003) and fallout from low-altitude suspension clouds (Sun et al., 2003), as measured from modern depositional events. This fraction requires less wind energy than EM1, is transported further, is more widely distributed, and therefore comprises a higher proportion of the distal~~ly~~ ~~deposited~~ loess populations ~~in loess generally~~ (Vandenberghe, 2013). We propose that EM2 was transported mainly in short-term, near-surface suspension during dust storms, and that wind strength controlled the relative proportions of EM1 and EM2 through time (see the mirror image relationships over millennial scales in Fig. 4).~~,~~ ~~which may implied~~ This interpretation implies that both EM1 and EM2 have a same origin.

The grain-size distribution of EM3 has a modal peak at 18.9 µm (Fig. 3b). This population belongs to '*subgroup 1.c.1*' in Vandenberghe (2013). This population is also widespread in loess from the CLP and NE-TP~~northeastern Tibetan Plateau~~ (Prins et al., 2007;Prins and Vriend, 2007), ~~and~~ the Danube Basin loess of Europe (Bokhorst et al., 2011;Varga, 2011).~~,~~ It is particularly common in loess of interglacial age (Vriend, 2007). There is as yet no consensus ~~as to~~regarding the transport processes responsible for this grain size population. On the one hand, researchers have suggested that grains of this size can be lifted by strong vertical air movement and subsequently incorporated into the high-level westerly air streams (Pye, 1995;Pye and Zhou, 1989). This process would link EM3 with long-term suspension transport driven by high-level Westerlies (Prins et al., 2007;Vriend et al., 2011;Nottebaum et al., 2014;Vandenberghe, 2013). Conversely, Zhang et al. (1999) argued that < 20 µm particle fractions ~~EM3~~ derives from "non-dust storm processes" associated with north-westerly surface winds. We argue for the latter on the basis that the EM3 modal grain size from the CLP and ~~northeast Tibetan Plateau~~NE-TP is coarser (Vriend et al., 2011) than EM3 at NLK in the Ili Valley, which is located further west. If EM3 was transported by high-level westerlies, then one would expect either no significant change (Rea et al., 1985;Rea and Hovan, 1995), or a decrease in grain size from west to east concomitant with wind direction. Furthermore, with mathematical fitting, Sun et al. (2004) related a fine component (2 – 8 μm) to high-altitude westerlies. This fine component is comparable to '*subgroup 1.c.2*' of Vandenberghe (2013), which is not consistent with ~~the~~ our modal size of EM3. Observations of modern aeolian processes at the southern margins of the Tarim Basin indicate that fine grain sizes similar to EM3 (8 − 15um) are deposited by settling during low velocity wind conditions (Lin et al., 2016). Particle-size distributions of background dust from the northern slopes of the Tianshan Mountains also typically yield a modal peak of approximately 10 μm (Schettler et al., 2014). We therefore infer the EM3 modal peak to derive from low altitude non-dust storm processes.

~~Other possibilities for the deposition of the fine~~ Fine particles can also be incorporated ~~include the incorporation~~ into silt- or sand-sized aggregates which can be transported by a range of wind velocities, including dust storms (Qiang et al., 2010;Pye, 1995;Derbyshire et al., 1998;Mason et al., 2003). For example, Ujvari et al. (2016) ~~indicated~~ argued that ~~the~~ ~ 1 – 20 μm fractions are affected by aggregation, as shown by comparison between minimally and fully dispersed grain size distribution~~s~~ measurements of loess samples from southern Hungary. Under higher wind velocity conditions, ~~the~~ aggregate ~~model~~ should co-vary with the coarser EM1 particles ~~which were~~ transported by surface winds during dust storms. However, since this model is unlikely to hold for EM3 particles (Fig. 4), the aggregate model is ~~not thought~~unlikely to be responsible for the presence of EM3 grain sizes ~~corresponding to EM3~~at NLK.

~~In addition, P~~Post-depositional processes may also influence grain size distribution. In large part this occurs ~~by~~ due to chemical weathering which produces very fine silt and clay minerals (Xiao et al., 1995;Wang et al., 2006;Hao et al., 2008).~~In particular, q~~ Quartz grains are more resistant to weathering ~~resistant~~ and remain largely unaltered during ~~the~~ post-depositional processes. Consequently, quartz mineral grain size may be used as a more reliable proxy indicator of winter monsoon strength than other components (Sun et al., 2006;Sun et al., 2000b;Xiao et al., 1995).

Figure. 6a shows the grain size distribution curves of quartz grains isolated from primary loess (yellow) and paleosol (red) samples. The quartz modal grain size is finer in the paleosol than in the primary loess unit. From this we can deduce that wind strength was weaker during pedogenesis, and stronger during periods of primary loess deposition. The grain size distributions of bulk samples display similar characteristics with those of quartz samples mentioned above (Fig. 6b), ~~whereby~~ since soil unit modal peaks (red and orange) are finer than those ~~for~~ in the primary loess (blue and green). Therefore, we argue that wind strength, rather than the post-depositional pedogenesis, has the greatest influence on grain size distribution at NLK, and that EM3 was ~~also~~ not produced by chemical weathering.

Fig. 6 Comparison of grain size distribution between purified quartz subsamples of paleosol and primary loess (a), and between bulk samples of paleosols and primary loess (b). Comparison of the grain size distribution between EM3 and samples from weak paleosol units (c).

The relative proportions of the end members down profile can yield ~~further~~ information about temporal variability in wind dynamics. The fairly consistent proportions of EM3 within the loess units indicate it to represent continuous background dust through time (Vandenberghe, 2013). Proportions of EM1 and EM2 decrease noticeably within paleosol units relative to EM3 (Fig. 4). This indicates that variations in proportions of EM3 are mainly driven by variability ~~of~~ in EM1 and EM2 (Vriend et al., 2011), but also that ~~a~~ consistent background sedimentation of EM3 ~~was~~

continued ~~dominant~~ during weak pedogenesis (Fig. 6c). This characteristic is comparable with observations from the CLP (Zhang et al., 1999).

In addition, small peaks at c. 0.8 µm are also observed in the grain-size distribution curves of all three end members. The generation of these finest grain peaks may be due to post-depositional pedogenesis (Sun, 2006), especially for ~~the~~ particles < ~~with grain-size smaller than~~ 2 µm (Bronger and Heinkele, 1990;Sun, 2006). However since the dominant modal peaks are much coarser ~~Nevertheless~~, weaker post-depositional weathering as suggested by MS is unlikely to have had a significant influence on the populations of EM1, EM2 or EM3 at NLK.~~,~~ ~~since the dominant modal peaks are much coarser.~~ Other potential sources include transportation as aggregates or by the finest grains adhering to coarser particles during transport. Regardless of cause, these particles are unlikely to yield meaningful information about wind regime variability or links to~~in westerly wind system strength~~ climate systems since they do not yield a clear independent end member peak.

### 5.3 Aeolian dust dynamics in eastern Central Asia: links to atmospheric systems

Variations in grain size through time at NLK were largely driven by changes in wind strength, without substantial influence of post-depositional pedogenesis. At NLK, grain size is therefore ~~is~~ an indicator ~~for~~ of loess response to ~~the atmospheric~~ climatic systems.

The three end members are interpreted to represent different depositional processes which operated throughout the accumulation of the deposit. The finer EM3 is interpreted to represent constant background dust, which continued to accumulate throughout periods of relative stability and pedogenesis. The coarser populations, EM1 and EM2, were transported by low-level winds during major dust storms. EM1 is most likely the most sensitive recorder of wind intensity, since EM2 is less sensitive to wind speeds than EM1 by observation of variations in EM2 proportions throughout L1S1 and L1L2 (Fig. 4).

Fig. 7 Comparison between EM1 grain size variability ~~with~~ and the timing of glacial advances in the Tien Shan (Koppes et al. 2008; Owen and Dortch, 2014); stable oxygen isotope variations from the Greenland ice cores (Rasmussen et al., 2014); mean grain size (MGS) record of the Jingyuan loess section from the CLP (Sun et al., 2010) and; U-ratio (15.6–63.4 µm/5.61–15.6 µm) of the SE Kazakhstan loess (Machalett et al., 2008). 5-point running average was performed for the intervals with higher sedimentary rate on EM1 curve (red line). ~~insolation values at 45°N (Berger and Loutre, 1991).~~

From ~~the~~ published OSL data (Song et al., 2015), we used linear regression (Stevens et al., 2016) to construct age–depth relationships over intervals of visually similar sedimentation rate (Fig. S4 and Table S1). ~~Based on the independent chronology sequences, we~~ We assessed the degree of correlation between wind strength variability in the Ili Valley (NLK), as represented by the proportions of EM1, with the stable oxygen isotope record from the Greenland ice cores representing North Atlantic paleoclimate (Rasmussen et al., 2014), the mean grain size (MGS) record of the Jingyuan loess section from the CLP (Sun et al., 2010), U-ratio (15.6–63.4 µm/5.61–15.6 µm) of the Remizovka loess section in SE Kazakhstan (Machalett et al., 2008), and glacial advances in the Tian Shan (Owen and Dortch, 2014;Koppes et al., 2008) ~~insolation values at 45°N and glacial advances in the Tian Shan~~ (Fig. 7).

~~In Fig. 7,~~ EM1 occurs in ~~larger~~ higher proportions during mid-MIS3, with a higher rate of sedimentary accumulation (Fig. 7). Glaciers in the region expanded during early- and late-MIS3

(Owen and Dortch, 2014). The apparent chronological link between increased primary loess accumulation and glacial expansion in the region contrasts with trends elsewhere indicating increased dust accumulation during dry-windy glacial conditions, and pedogenesis under comparatively wetter interglacial conditions ~~Generally dust is assumed to be generated, and deposited, during dry-windy glacial conditions, while interglacial conditions were comparatively wetter and more conductive to pedogenesis~~ (Stevens et al., 2013;Sun et al., 2010;Ding et al., 2002;Dodonov and Baiguzina, 1995). ~~By contrast,~~Our observations suggest a seesaw relationship between increased loess accumulation ~~rapid loess deposition~~ and glacial expansion ~~was observed~~ during MIS3 ~~from our results~~ (Fig. 7), a model supportedt ~~hat has also been noticed~~ by Youn et al. (2014). ~~The mass accumulation rate (MAR) of loess is good proxy for aridity , while moisture~~ Moisture availability appears to be~~is~~ the dominant factor controlling glacier growth in Central Asia, especially for glaciers in the Tian Shan (Zech, 2012;Koppes et al., 2008). We infer, therefore, that moisture had an important impact on accumulation of dust in the study area ~~over~~ during MIS3 in particular.

Central Asia is variably influenced by the Asian monsoon from the south (Dettman et al., 2001;Cheng et al., 2012), the mid-latitude westerlies (Vandenberghe et al., 2006), the Siberian high-pressure systems from the northeast (Youn et al., 2014), and the polar front from the north (Machalett et al., 2008). ~~However, by virtue of its geographical position, most of these climate influences can be excluded for the Ili Valley since it is sheltered to the northeast, east and south.~~. The Asian high mountains largely inhibit the intrusion of Asian (Indian and East Asian) monsoons to the region, since the Ili Valley is sheltered to the northeast, east and south. Studies of the oxygen isotopic composition of precipitation in the Tian Shan Mountains region support this geographic situation by indicating a stronger connection with westerly circulation than with the Asian summer monsoon (Liu et al., 2015;Chen et al., 2016)~~and the influence of the Siberian High has been shown to decrease westward from the CLP~~.

Modern satellite data indicates that dust storm development in Ili river valley is closely linked with southward-moving high-latitude air masses (Ye et al., 2003). The large, cold Siberian High pressure system is at the north-northeast of our study area, centring between 40°N and 65°N, 80°E and 120°E (cf. Fig. 3 in Huang et al. (2011)). The Siberian anticyclone dominates winter and spring climate over Eurasia (Sahsamanoglou et al., 1991;Savelieva et al., 2000;Panagiotopoulos et al., 2005;Gong and Ho, 2002;Obreht et al., 2017). Although the influence of the Siberian High has been shown to decrease westward from the CLP (Vandenberghe et al., 2006), wind strength and frequency over the Aral Sea in western central Asia during the Holocene was nevertheless associated with the intensity of the Siberian High pressure system (Huang et al., 2011;Sorrel et al., 2007). Obreht et al. (2017) even hypothesized increased influence of the Siberian High during MIS3 over the Lower Danube Basin in SE Europe, although this has yet to be substantiated. Moreover, the Siberian High was considered to be one of the most important influences on dust deposition based on the results of long-term monitoring over Central Asia between 2003 and 2010 (Groll et al., 2013).

Increases in modal grain-size from the CLP are also linked to a strengthened East Asian winter monsoon due to intensification of the Siberian High (Ding et al., 1995;Hao et al., 2012). Therefore, the grain-size record from the Chinese loess is a likely indicator of Siberian High intensity. We use the Jingyuan loess section as a point of comparison in our study, because it is a high resolution record located in the northwestern CLP, with high sedimentation rate, and thus the likelihood of preservation of millennial-scale oscillations. We compared secular trends between the EM1 proportions and MGS data from Jingyuan over the last glacial period (Sun et al., 2010). Similarities can be observed (Fig. 7); coarser grain sizes and higher sedimentation rates are observed during mid-MIS3 (Sun et al., 2010), with the opposite occurring in early- and late-MIS3. This supports a common Eurasian atmospheric forcing pattern - the Siberian High - driving the climate evolution of the Ili Basin and CLP during that time period.

By comparison, the Last Glacial Maximum (LGM) witnesses significantly different trends, despite increased sedimentation rates (Sun et al., 2010) (Fig. 7). EM1 proportions decrease particularly during the early-LGM. We attribute this to a reduction in sediment supply, possibly linked to permafrost development in the Ili Basin and Kazakhstan steppe (Fig. 1) (Zhao et al., 2014;Vandenberghe et al., 2014). Reduced sediment supply therefore limits the degree to which grain-size characteristics can reliably indicate wind strength during the LGM.

Machalett et al. (2008), presenting data from the Remizovka site in the more open western Ili Basin, argued that the Arctic polar front, expanding southward in winter and retracting northward in summer, most likely increased the frequency and strength of cyclonic storms due to higher temperature and humidity gradients created between colder polar air and warmer tropical air (Harman, 1991). They hypothesized that this climate system was the predominant influence on dust transport and loess accumulation during cold phases along the Kyrgyz (southern) Tian Shan piedmont. While this may have been the case at Remizovka, it is unlikely to have affected NLK in the eastern Ili Basin, however, since the eastern basin is much more sheltered due to the position of the mountain ranges (Fig. 1a).

To assess spatial variability in climatic influence across the Ili Basin, we compare EM1 curve with U-ratio (15.6–63.4 μm/5.61–15.6 μm) of the polar-front-influenced Remizovka loess. We observe minimal similarities in the curves. These disparities suggest that two different atmospheric forcing patterns controlled loess accumulation from one end of the Ili Basin to the other. The differences appear to be particularly clear over MIS3, respectively (Fig. 7), although problems with chronological integrity at the Remizovka site need to be resolved (Fitzsimmons et al., 2016) before we can argue this with confidence. In addition, U-ratios decrease during the LGM (Fig. 7), supporting our hypothesis that the development of permafrost limits the availability of source sediments for loess in this region.

We argue that the Siberian high-pressure system exerts a significant influence on wind dynamics and loess deposition in the eastern Ili Basin. It is evident that the strongest winds at NLK site mainly blow from the west (Table S2), although northerly high-latitude air masses with potential for short-term dust transport can enter the Ili Basin by deflection around the northern Tian Shan (Fig. S5).

Enhanced evaporation, coupled with strengthened westerly winds, would bring more humid and warmer conditions to ACA during the Holocene (Zhang et al., 2016). Karger et al. (2016) reconstructed the dynamics of the westerlies in the Ili Basin, proposing a rain belt which seasonally migrates towards the south and north in autumn and summer, respectively. A strengthened Siberian High would push the mid-latitude Westerlies pathways further to the south, resulting in comparably drier conditions in northeastern Central Asia (e.g. Tian Shan) but wetter conditions in southwestern Central Asia (Pamir) (Lei et al., 2014;Wolff et al., 2017). The intensity and geographical position of the Siberian High would most likely impact precipitation and atmospheric circulation patterns (meridional or zonal) in the mid-latitudes Central Asian (Panagiotopoulos et al., 2005). It is therefore most likely that, the mid-latitude Westerlies controlled broad-scale patterns of moisture variation across ACA broadly (Huang et al., 2015;Li et al., 2011;Cai et al., 2017), whereas the eastern Ili Basin experienced the combined influence of the Siberian High and the mid-latitude Westerlies system.

~~Modern satellite data indicates that dust storm development in Ili river valley is closely linked with southward-moving high-latitude air masses . provided a detailed picture of the westerlies for the Ili Basin, in which a rain belt gradually migrated towards the south and north in autumn and summer, respectively. According to this scenario, enhanced evaporation coupled with strengthened westerly winds would bring more humid and warm air masses to Arid Central Asia (ACA) during the Holocene . Therefore, based on our grain-size observations, we argue that the Arctic polar front, intruding southward in the winter and retracting northward in summer , most likely increased the frequency and strength of cyclonic storms, leading to dust transport and the accumulation of loess deposits during cold phases when it predominated in the Ili Basin and along the Kyrgyz Tian Shan piedmont. While the mid-latitude westerlies increasingly influenced the climate in this region as the climate became warmer when the polar front shifted northward, and controlled the patterns of moisture variations .~~

~~Comparison of EM1 proportions with variability in June insolation at 45ºN shows a distinct correlative relationship on the orbital timescale (Fig. 7), which indicates local insolation-based control on wind dynamics. When the insolation values increases, the rising of temperature, as a result, enhances the frequency or strength of cyclonic storms, resulting in higher sedimentary rates or higher coarse-grain proportions (Fig. 7). However, EM1 proportions exhibit more substantial fluctuations than may be attributed to insolation values during the mid- and late-MIS3. We ascribe that to the humidity variations in the study area. In the early-MIS 3, increased moistures due to migration of westerlies towards the north were conducive to vegetation growth in source areas, which reduced sediment entrainment and resulted in less contribution of coarse grains to loess site, though glacial grinding of rocks in the high mountains could produce amount of fine-grained materials . Whereas arid environment in the mid-MIS 3, observed by a lack of glacial advance in Tian Shan (Fig. 7) and also reflected by the increased MAR (Fig. 7) , likely made these sediments with coarser grain size produced in the early-MIS 3 available as the source materials for NLK loess, as the case in the north-eastern Tibetan Plateau .~~

~~Over millennial scales, our grain-size proxy data do not correlate strongly with abrupt events, such as H1, H2, H3 and H5, identified from the North Atlantic records (Fig. 7). Some of the peaks in EM1 curve correspond to valleys in GISP~~ $\delta^{18}O$ ~~curve (black arrows in Fig. 7), yet many do not.~~

~~Grain size studies of the Darai Kalon loess section in Tajikistan, 1200 km to the southwest of NLK, inferred a strong influence from the westerlies resulting in transport of the North Atlantic signal to the East Asia . Darai Kalon is, however, located in a region where the mid-latitude westerlies clearly have a much stronger influence. Our results from the Ili Basin contradict those of , which suggest that the mid-latitude westerlies probably did not predominate north of the Kyrgyz Tian Shan. In this case, the high mountains in Central Asia most likely obstructed the migration of the Asiatic polar front further south towards Tajikistan where those data were derived, thereby resulting in a stronger westerlies signal at Darai Kalon than at NLK.~~

~~Our results also contradict those of , who proposed that millennial-scale North Atlantic climate signals might have been transmitted to the Siberian High via the Barents and Kara Sea ice sheets, and then propagated eastwards to the Chinese Loess Plateau via the winter monsoon system. In our~~

~~case, the influence from northern climate subsystems such as the Siberian High or polar front appear not to have transmitted millennial-scale North Atlantic climatic events, maybe supporting the significance of the westerlies in transmitting North Atlantic climate signals to East Asia.~~

Comparison of EM1 proportions with variability in GISP $\delta^{18}O$ suggests that our grain-size proxy data may correlate with abrupt events, such as North Atlantic Heinrich events H1 to H6 (Fig. 7), although this correlation cannot yet be better constrained due to limitations in the chronological dataset. Some of the peaks in EM1 curve correspond to troughs in GISP $\delta^{18}O$ curve (black arrows in Fig. 7) outside Heinrich events, yet many do not (pink dashed lines in Fig. 7). Potential causes of this discrepancy may lie in variability in local source availability and wind dynamics at certain points in time.

Comparisons between the eastern Ili Basin and Chinese Loess Plateau loess further elucidates complexity in the climatic signal preserved in the ACA. The NLK EM1 proportions in the Ili Basin yield lower variability than the Jingyuan MGS on the CLP, particularly during H2 and H5 (Fig. 7). We attribute these differences to local source sediment availability at NLK. EM1 supply to NLK was reduced during H2 due to the development of permafrost, and during H5 due to increased vegetation cover associated with more humid conditions inhibiting coarse-grain entrainment (Fig. 7). By contrast, the relatively more arid mid-MIS 3, indicated by glacial retreat in the Tian Shan, may have decreased vegetation cover and increased entrainment potential and transport to NLK (Fig. 7); these conditions and this trend was also observed in the NE-TP (Vriend et al., 2011). The differences may be because the loess records in our study area represent a response not only to hemispheric climate systems, but also to local influences such as local atmospheric circulation and topography. Since the sedimentary response to changing climate conditions in more arid Central Asia is different to that of the more temperate European loess (Rousseau et al., 2007), we must be careful about investigating the mechanisms of aeolian dynamics and loess accumulation in our paleoclimatic interpretations of ACA loess archives.

Many studies have speculate that millennial-scale oscillations represent a teleconnection between the North Atlantic and East Asia (e.g. Porter and An, 1995; Yang and Ding, 2014), although the dynamics involved are poorly understood. Porter and An (1995) and Sun et al. (2012) suggested, based on CLP loess physical characteristics, that a strong influence from the westerlies resulted in transport of the North Atlantic signal to East Asia. Conversely, Yang and Ding (2014) proposed that millennial-scale North Atlantic climate signals might have been transmitted to the Siberian High via the Barents and Kara Sea ice sheets, and were propagated eastwards to the CLP via the winter monsoon system. In the western CLP (Chen et al., 1997a), for example, evidence of millennial-scale (likely Heinrich) events are preserved within the loess stratigraphy during phases of strong winter monsoon in China; however, not all of the strong winter monsoon events in China correlate with Heinrich events in the North Atlantic, so challenging the Yang and Ding (2014) hypothesis.

Stronger datasets from Central Asia may provide the missing link for understanding climate teleconnections between the two extreme ends of the Eurasian continent. In doing so, however, the scale of the “Central Asian” region must be taken into account. At Darai Kalon in Tajikistan, 1200 km southwest of NLK, the mid-latitude westerlies clearly have a strong influence on dust transport and loess accumulation; Atlantic signals are clearly identified in grain size variations, especially during full glacial phases (Vandenberghe et al., 2006). Since the CLP lies at a similar latitude to Darai Kalon, mid-latitude Westerlies have the potential to transport North Atlantic climate signals to East Asia. By contrast, since NLK is located substantially further north than Darai Kalon and the

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CLP, the Siberian High exerts a greater influence on wind dynamics and therefore loess deposits. A strengthened Siberian High would effect a southward shift of the mid-latitude Westerlies pathways; under such conditions, NLK would be less strongly influenced by the mid-latitude westerlies. This argument is further supposed by the lack of correlation between NLK EM1 proportions and GISP $\delta^{18}O$ values during relatively mild interstadial periods (Dansgaard-Oeschger cycles) when the mid-latitude westerlies shift northwards (Fig. 7). Therefore, NLK provides a strategic location for investigating the potential role of the Siberian High in transmitting North Atlantic climate signals to East Asia. The preservation of North Atlantic several millennial-scale Heinrich events at NLK supports the argument for the influence of the Siberian High as argued by Yang and Ding (2014).

## Conclusion

~~In this study,~~ Our data from NLK in the eastern Ili Basin provides a paleoenvironmental record over the last c, 70 ky~~for the last glacial from the Nilka (NLK) loess section in Ili Basin was provided~~. The magnetic properties of the loess do not correlate with ~~indicate that no strong~~ pedogenesis ~~occurred~~ in this section; rather~~, even in the paleosol units. Variations in magnetic susceptibility (MS) value closely correlate with the proportions of sand fraction, and~~, wind strength is mainly responsible for ~~those~~ variations in physical characteristics ~~since~~ over the last glacial period.

~~With the unmixing of grain size distributions, t~~Three grain-size end members were ~~distinguished~~identified at NLK: EM1 (mode size at 47.5 μm), EM2 (33.6 μm) and EM3 (18.9 μm). They are indicative of different kinds of depositional processes which operated throughout the accumulation of the loess ~~deposit at NLK section~~. EM1 and EM2 represent~~ed the~~ grain-size fractions transported from proximal sources in short-term, near-surface suspension during dust outbreaks~~.~~ ~~They~~, and may have the same origin. While wind strength their controls relative proportions, EM1 is ~~most likely~~ the most sensitive recorder of wind strength. EM3 represents continuous background dust under ~~the~~ non-dust storm processes.

The Siberian High-pressure system predominates in the eastern Ili Basin during cold phases, which leads to dust transport and increased loess accumulation at NLK. Many rapid cooling events, including 6 Heinrich events, were imprinted in the NLK loess. Our grain-size data support the argument that the Siberian High plays a significant role in transporting North Atlantic climatic signals to East Asia via ice sheets in the high northern latitudes.

~~The Arctic polar front predominates in the Ili Basin and the Kyrgyz Tian Shan piedmont during cold phases, which leads to the dust transport and increased accumulation of loess deposits, while the shift of mid-latitude westerlies towards the south and north controlled the patterns of precipitation/moisture variations in this region. On the orbital scale, the local insolation-based control has an important impact on wind dynamics directly related to accumulation of loess, and moisture can may also influence grain size of loess in the study area over MIS3 in particular. Although, the polar front dominated wind dynamics for loess deposition in the Ili Basin and the Kyrgyz Tian Shan, the Central Asian high mountains obstructed its migration further south. Our results may also support the significance of the mid-latitude westerlies in transmitting North Atlantic climate signals to East Asia.~~

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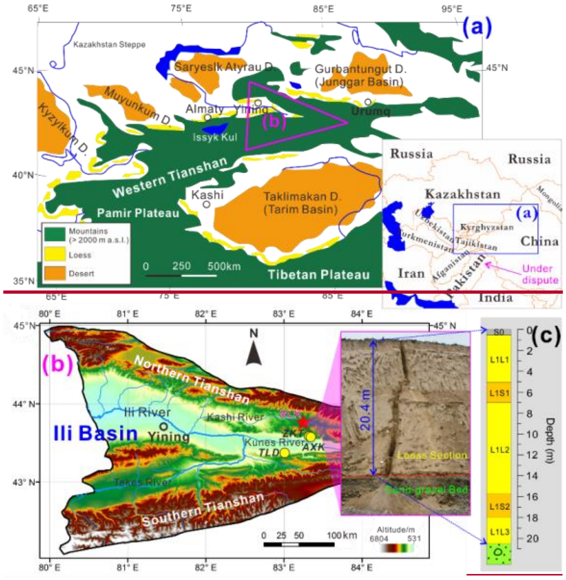
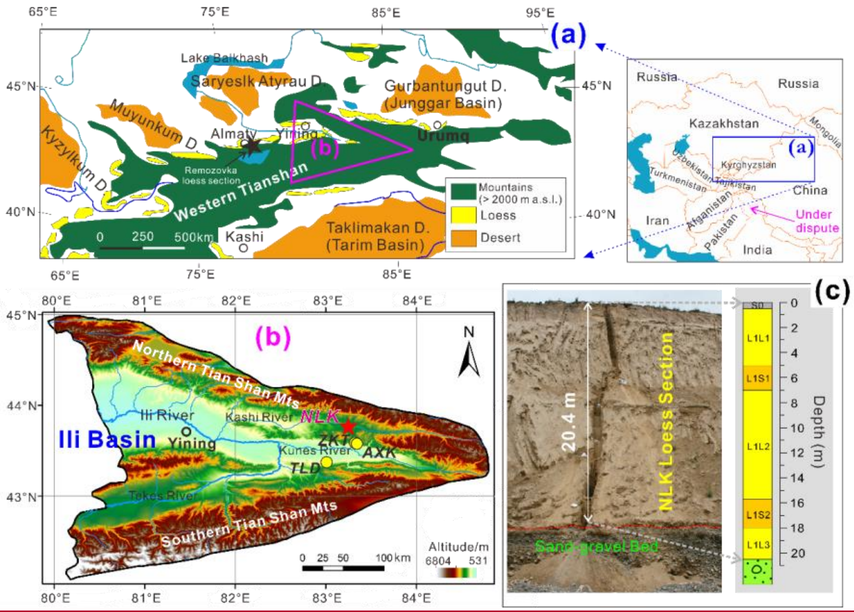
Fig01

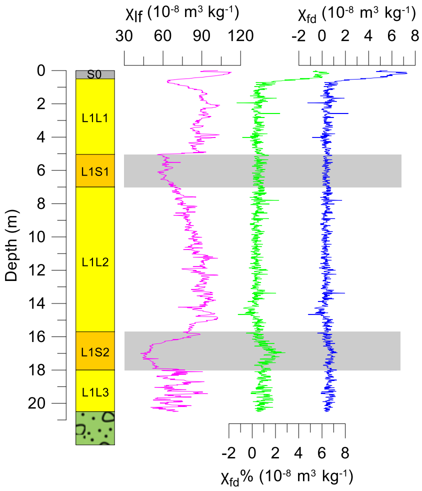


(a)
Kazakhstan Steppe
Saryeslk Atyrau D.
Gurbantungut D.
(Junggar Basin)
Muyunkum D.
Almaty
Yining
Urumq
(b)
Issyk Kul
Kyzylkum D.
Western Tianshan
Pamir Plateau
Kashi
Taklimakan D.
(Tarim Basin)
Tibetan Plateau
Mountains
(> 2000 m a.s.l.)
Loess
Desert
0 250 500km
Russia
Kazakhstan
Kyrghyzstan
Tajikistan
China
Iran
India
Under dispute
(b)
Northern Tianshan
Ili River
Kashi River
Ili Basin
Yining
Kunes River
ZKT
AXK
TLD
Tekes River
Southern Tianshan
0 25 50 100km
Altitude/m
6804 531
20.4 m
Loess Section
Sand-gravel Bed
(c)
Depth (m)
S0
L1L1
L1S1
L1L2
L1S2
L1L3

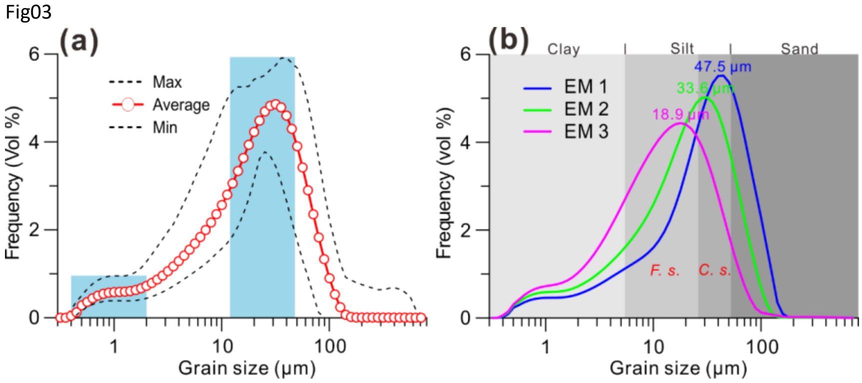
(a)
Lake Balkhash
Saryeslk Atyrau D.
Gurbantungut D.
(Junggar Basin)
Muyunkum D.
Almaty
Yining
(b)
Urumq
Kyzylkum D.
Remozovka
loess section
Western Tianshan
Mountains
(> 2000 m a.s.l.)
Loess
Desert
0 250 500km
Kashi
Taklimakan D.
(Tarim Basin)
Russia
Kazakhstan
Kyrgyzstan
China
Iran
India
Under dispute
(b)
Northern Tian Shan Mts
Ili River
Kashi River
NLK
Ili Basin
Yining
Kunes River
ZKT
AXK
TLD
Tekes River
Southern Tian Shan Mts
0 25 50 100km
Altitude/m
6804 531
(c)
20.4 m
NLK Loess Section
Sand-gravel Bed
Depth (m)
S0
L1L1
L1S1
L1L2
L1S2
L1L3

Fig02



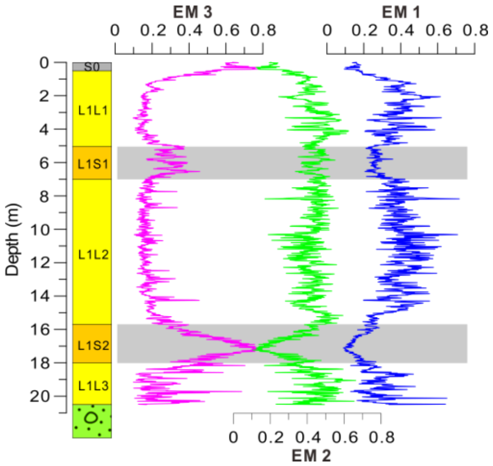
χlf (10-8 m3 kg-1)
30 60 90 120
χfd (10-8 m3 kg-1)
-2 0 2 4 6 8
Depth (m)
0 2 4 6 8 10 12 14 16 18 20
S0
L1L1
L1S1
L1L2
L1S2
L1L3
-2 0 2 4 6 8
χfd% (10-8 m3 kg-1)

Fig03



(a)
Max
Average
Min
Frequency (Vol %)
Grain size (μm)
0
2
4
6
1
10
100
(b)
Clay
Silt
Sand
EM 1
EM 2
EM 3
47.5 μm
33.6 μm
18.9 μm
F. s.
C. s.
Frequency (vol %)
Grain size (μm)
0
2
4
6
1
10
100

Fig04



EM 3
0 0.2 0.4 0.6 0.8
EM 1
0 0.2 0.4 0.6 0.8
Depth (m)
0
2
4
6
8
10
12
14
16
18
20
S0
L1L1
L1S1
L1L2
L1S2
L1L3
0 0.2 0.4 0.6 0.8
EM 2

Fig05

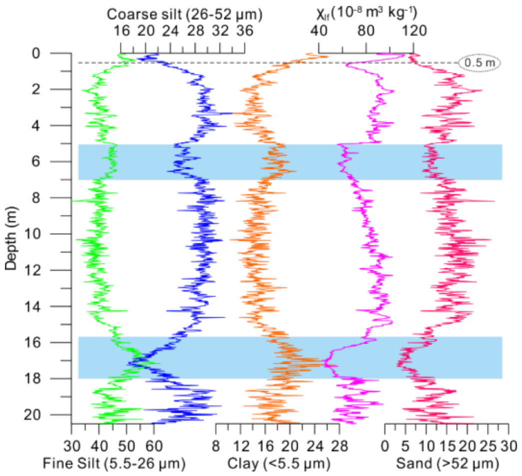
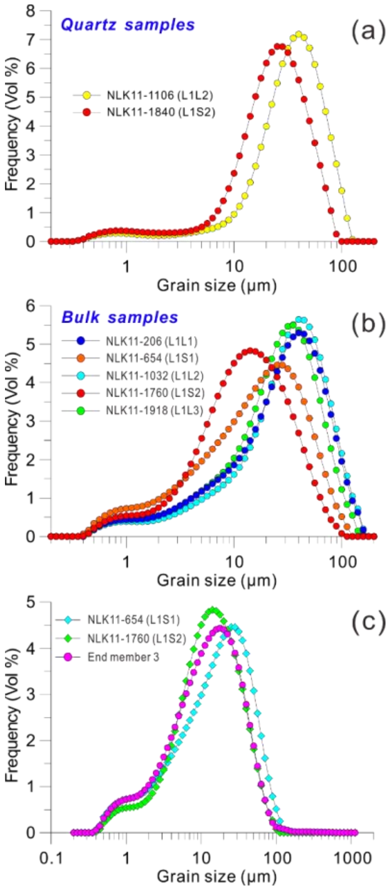
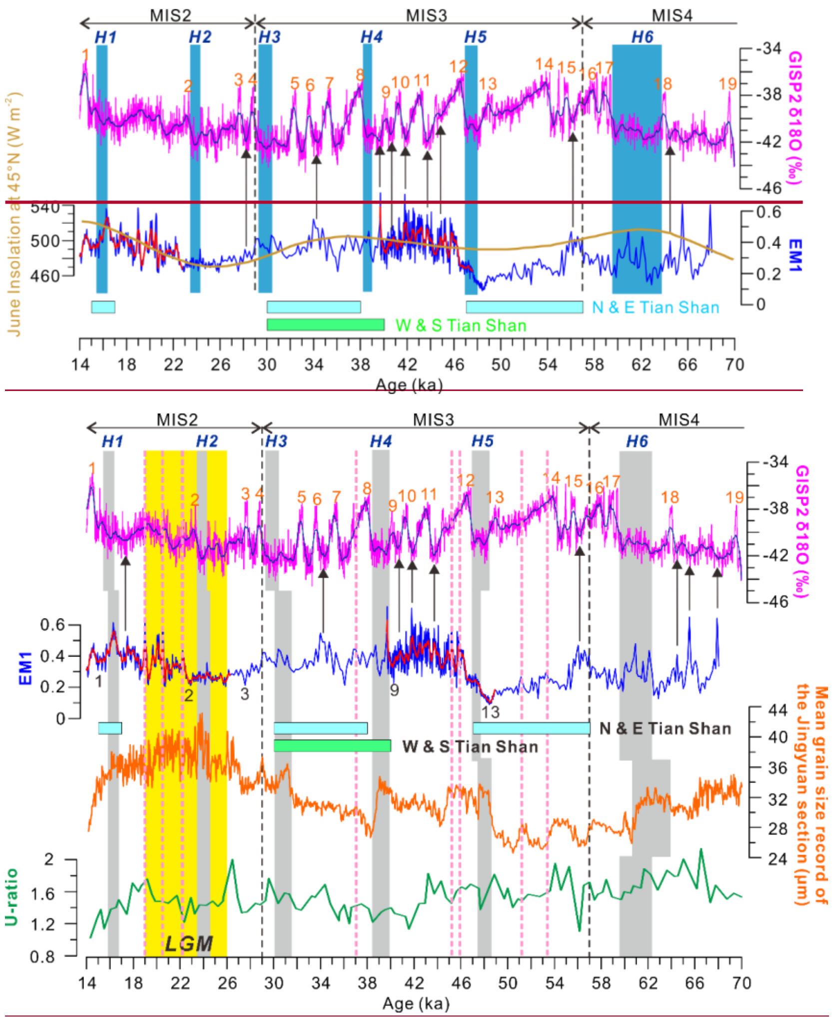

Coarse silt (26-52 μm)
16 20 24 28 32 36
χlf (10-8 m3 kg-1)
40 80 120
0.5 m
Depth (m)
0 2 4 6 8 10 12 14 16 18 20
30 40 50 60
Fine Silt (5.5-26 μm)
8 12 16 20 24 28
Clay (<5.5 μm)
0 5 10 15 20 25 30
Sand (>52 μm)

Fig06



Quartz samples
(a)
NLK11-1106 (L1L2)
NLK11-1840 (L1S2)
Frequency (Vol %)
Grain size (μm)
Bulk samples
(b)
NLK11-206 (L1L1)
NLK11-654 (L1S1)
NLK11-1032 (L1L2)
NLK11-1760 (L1S2)
NLK11-1918 (L1L3)
Frequency (Vol %)
Grain size (μm)
(c)
NLK11-654 (L1S1)
NLK11-1760 (L1S2)
End member 3
Frequency (Vol %)
Grain size (μm)

Fig07



MIS2
MIS3
MIS4
H1
H2
H3
H4
H5
H6
GISP2 δ18O (‰)
EM1
June Insolation at 45°N (W m⁻²)
N & E Tian Shan
W & S Tian Shan
Age (ka)
Mean grain size record of the Jingyuan section (μm)
U-ratio
LGM