Northern Hemisphere ice sheet expansion intensified Asian aridification and the winter monsoon across the mid-Pleistocene transition

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Abstract

The mid-Pleistocene transition (MPT) from ~1.25 to ~0.6 million years ago (Ma) marked a major shift in periodicity of Earth's climate variability from dominantly ~40- to ~100-thousand years (kyr) without a concomitant shift in orbital forcing. Here we advance understanding of Asian climate dynamics associated with two glacial extreme loess coarsening events that are recorded across the Chinese Loess Plateau (CLP) at the onset and middle of the MPT. This is based on a combination of new and existing millennial-resolution grain size and magnetic susceptibility records for the last 1.6 million years from the CLP and general circulation model simulations, viewed within a global palaeoclimatological context. We find that the two extreme glacial events reflect exceptionally enhanced Asian aridification and winter monsoon activity. They occurred at times of notable Northern Hemisphere glacial ice sheet expansion, when the ~100-kyr glacial cyclicity initiated and intensified at marine isotope stages 38 and 22 (~1.25 and ~0.9 Ma), respectively. Our integration of palaeoclimate data and climate model simulations indicates that these anomalously cold, dry, and windy Asian glacials were driven by amplified, non-linear regional threshold responses to phases of Northern Hemisphere ice sheet expansion.

Introduction

Earth's orbital variations drove periodic Pleistocene climate oscillations between glacial and interglacial conditions\(^1\)–\(^4\). During cold glacials, continental-scale ice sheets developed in mid- to high-latitude North America and Eurasia, and the Antarctic Ice Sheet expanded beyond its present-day margins\(^5\)–\(^7\). These ice sheets "retreated" to present-day configurations, or beyond, during warm interglacials\(^5\)–\(^7\). Glacial oscillations notably transitioned from a lower-amplitude ~40-thousand years (kyr) cyclicity to higher-amplitude ~100-kyr cyclicity between ~1.25 and ~0.6 million years ago (Ma)\(^6\),\(^8\)–\(^13\). This major climatic event, known as the mid-Pleistocene transition (MPT), featured a substantial Northern Hemisphere ice sheet expansion\(^6\),\(^8\)–\(^13\), and was accompanied by ocean thermohaline circulation weakening at ~0.9 Ma\(^14\),\(^15\). However, continuous high-resolution terrestrial records through the MPT are rare, which hinders comprehensive understanding of the nature and drivers of the MPT\(^11\),\(^12\). After more than two decades of research, the drivers of climate change across the MPT remain debated\(^11\),\(^12\).

The ~640,000 km\(^2\) Chinese Loess Plateau (CLP) extends across the northeastern Tibetan Plateau margin from ~100 to 115°E and from ~34 to 41°N (Fig. 1). It contains a thick aeolian loess-palaeosol sequence that spans the MPT continuously. These aeolian sediments were transported from the inland Gobi Desert, other nearby sandy deserts, and poorly-vegetated areas by near-surface northwesterly winter monsoon winds\(^16\) (Fig. 1a). Winter monsoon winds are caused by the outflow of cold and dry air from high pressure cells over the cool Asian continental interior, which blow toward lower pressure cells over the warmer West Pacific and North Indian Oceans. Strong winter monsoons during global glacials resulted in deposition of thick loess layers; they consist of a mixture of clays, silts, and fine sands, and are largely unaltered by pedogenesis, with a yellow colour\(^17\),\(^18\). The Asian summer monsoon transports heat and moisture from the West Pacific and Indian Oceans toward intense low-pressure (warm) cells over South
and East Asia during the boreal summer. Enhanced summer monsoon precipitation on the CLP during global interglacials drove more intense pedogenesis, formation of abundant iron oxides (e.g., magnetite, maghemite, and hematite), red soil development within the yellow loess sequence\textsuperscript{19–21}. Shift from yellow to red is caused dominantly by increased red hematite formation during intense pedogenesis\textsuperscript{22}. Resultant cyclic alternations between yellow loess and red palaeosol layers are comparable across North China\textsuperscript{18–20,23}, which provide a unique, continuous continental archive of orbital- to millennial-scale Asian monsoon and environmental variability. Furthermore, they shed light on both low- and high-latitude processes (i.e., summer and winter monsoon, respectively), which can be used to understand the relationship between global and regional Asian climate changes across the MPT\textsuperscript{17–29}.

We aim to improve understanding of orbital-scale Asian climate variability and dynamics that are linked to global change during the ‘100-kyr world’ development across the MPT. For this, we present new millennial-resolution palaeoclimate records that span the last 1.6 Myr from two parallel loess-palaeosol sections on the central CLP, and investigate glacial-interglacial changes in the winter monsoon, summer monsoon, dust and moisture transport, and Asian interior climatic conditions across the MPT, with particular focus on two extreme pulses. We consider these CLP palaeoclimate records within context of existing terrestrial and global palaeoclimate records. We also perform new Earth System model simulations to assess the influence of Northern Hemisphere ice sheet expansion in driving the observed continental-scale Asian glacial climate anomalies across the MPT.

**Results And Discussion**

**Insights from CLP palaeoclimate records.** The grain size of the Quaternary CLP loess-palaeosol sequences reflect dust transport by winter monsoon winds and is generally interpreted as a winter monsoon intensity indicator\textsuperscript{20,23,30}. We measured the grain size distribution of the Luochuan (109°24′E, 35°48′N) and Chaona (107°12′E, 35°7′N) loess-palaeosol sections on the central CLP (Fig. 1) to investigate winter monsoon dust transport evolution over the last 1.6 Myr. Similar to the global chronology for benthic foraminiferal δ\textsuperscript{18}O records from marine sediment cores\textsuperscript{31}, the loess-palaeosol chronology has been established based on different sections/cores across the CLP using orbital tuning, land-sea correlation, and/or grain-size age models, which result in similar ages and the same correlations of loess and palaeosol layers to glacial and interglacial periods defined by the marine benthic δ\textsuperscript{18}O record\textsuperscript{18,20,23,28,32}. Chronological uncertainties do not result in major differences in loess-to-marine correlations across a glacial-interglacial cyclicity. Our CLP loess-palaeosol chronology was established by combined palaeomagnetic and pedostratigraphic constrains and correlations of Luochuan and Chaona median grain size and magnetic susceptibility (χ) records to the marine benthic foraminiferal δ\textsuperscript{18}O record (see Methods and Supplementary Fig. 1 for details). Other CLP loess-palaeosol sections were also synchronized to this chronology (Figs. 2 and 3). Our new median grain size records from the Chaona and Luochuan sections have consistent glacial-interglacial variabilities that are also comparable with those from other sections across the CLP (Fig. 2). To reduce the effects of local changes, and to better reveal large-scale glacial-interglacial winter monsoon dust transport across the CLP, we compile a median grain
size stack based on our new records from Chaona and Luochuan sections and existing records from the Lingtai \textsuperscript{18}, Jingchuan \textsuperscript{18}, and Baicaoyuan \textsuperscript{33} (Fig. 2; Methods).

Summer monsoon precipitation contributes 60–75% of annual precipitation on the CLP and its variations have major impacts on regional environmental conditions \textsuperscript{19}. CLP loess-palaeosol $\chi$ is a much-used proxy for summer monsoon precipitation because stronger pedogenesis during periods of increased precipitation accelerates fine magnetite/maghemite and hematite formation that causes higher $\chi$ values \textsuperscript{20,21,34}. To assess summer monsoon variability on the CLP coeval to our grain-size-based winter monsoon record, we compose our new loess-palaeosol $\chi$ stack by compiling existing $\chi$ records from Luochuan \textsuperscript{32}, Chaona \textsuperscript{27}, Jingchuan \textsuperscript{35}, Zhaojiachuan \textsuperscript{23}, Lantian \textsuperscript{36}, and Lingtai \textsuperscript{23} (Fig. 3). Like median grain size, temporal $\chi$ variability matches well among sections and generally correlates cycle-to-cycle with glacial-interglacial cycles in the benthic foraminiferal $\delta^{18}O$ record (Figs. 2–3). Nevertheless, the records contain subtle differences in their details, largely because they represent distinct climate variables (i.e., summer monsoon precipitation for $\chi$, winter monsoon intensity for grain size, and deep-sea temperature and global ice volume for benthic foraminiferal $\delta^{18}O$).

Consistent with previous studies \textsuperscript{18,20,23,24,28}, glacial loess layers have larger median grain sizes (stronger winter monsoons) and lower $\chi$ values (weaker summer monsoons and lower precipitation) than interglacial palaeosol layers (Figs. 2–4). Notably, loess layers L\textsubscript{15} (correlating to MIS 38 at \sim 1.25 Ma) and L\textsubscript{9–1} (correlating to MIS 22 at \sim 0.9 Ma) have notably lower $\chi$ values and exceptionally larger median grain sizes than other loess layers (Fig. 4a–b). The distinct grain size increases in L\textsubscript{15} and L\textsubscript{9–1} are observed in all loess-palaeosol sequences from both the eastern and western CLP (Fig. 2), which indicates dominant and widespread dust transport changes over a large areal extent during MIS 38 and MIS 22 across the entire CLP. We infer that winter monsoon conditions over Asia during these periods were amplified (i.e., cooler, drier, and windier) compared to preceding and succeeding glacials.

To investigate the main (orbital) periodicities of the Asian summer and winter monsoon, and to compare these to the global (i.e., high-latitude) climatic response, we present time-evolutive spectral analyses of the $\chi$, grain size, and marine benthic foraminiferal $\delta^{18}O$ stacks. Spectral analyses of the median grain size and $\chi$ stacks suggest a major transition from a predominant \~ 40-kyr to \~ 100-kyr periodicity across the MPT, albeit with subtle differences in the exact expression of the transition (Fig. 5a–b). These differences likely reflect more nuanced regional response differences to MPT climate change. CLP precipitation (indicated by $\chi$) is dominated by moisture transport from the West Pacific and Indian Oceans to inland Asia by the summer monsoon, which is a low-latitude process, whereas transport of cold and dry air from high-latitude Eurasia toward the tropical oceans by the winter monsoon (indicated by median grain size) represents a high- to mid-latitude process. Spectral analyses of the benthic foraminiferal $\delta^{18}O$ record \textsuperscript{31} reveal a prominent switch from predominant \~ 40-kyr to \~ 100-kyr cycles across the MPT, with combined \~ 40-kyr and \~ 100-kyr cycles between \sim 1.2 Ma and \sim 0.6 Ma (Fig. 5c). Weakened continuation of obliquity (\~ 40-kyr) cyclicity until \sim 0.6 Ma suggests that the major MPT periodicity shift was more gradual and delayed in the global mean glacial cycle pattern reflected in the
benthic foraminiferal $\delta^{18}$O relative to the CLP precipitation ($\chi$) and winter monsoon (median grain size) records (Fig. 5).

**Mechanism of distinct loess coarsening throughout the CLP across the MPT.** Our new grain size records reveal broadly consistent orbital-scale variability and extreme pulses across the MPT as documented in previous records\textsuperscript{18,23−25}. Prominent loess grain size anomalies at $\sim 1.25$ Ma (L\textsubscript{15}) and $\sim 0.9$ Ma (L\textsubscript{9−1}) have been explained previously in terms of phased Tibetan Plateau uplift\textsuperscript{24}. However, evidence for major plateau uplift during the MPT is tenuous. The Tibetan Plateau was already close to its present-day elevation and configuration at least in the late Miocene, with only limited and more regional Quaternary adjustments\textsuperscript{37−42}. Thus, plateau uplift cannot explain the distinct coarsening of L\textsubscript{15} and L\textsubscript{9−1} across the CLP, nor explain their astronomical pacing. This leaves the cause(s) of L\textsubscript{15} and L\textsubscript{9−1}, and their palaeoclimatic significance, open to further investigation\textsuperscript{18}.

In contrast to the Tibetan Plateau uplift interpretation\textsuperscript{24} and other CLP studies that focused on the MPT shift in orbital periodicities\textsuperscript{26−29}, we assess the distinct loess coarsening of L\textsubscript{15} and L\textsubscript{9−1} across the CLP from first principles, and within a global context. Fundamentally, these exceptionally coarse loess layers must reflect a combination of (i) widespread wind strength increase, (ii) transport pathway shortening due to enhanced and expanded central Asian aridity, (iii) enhanced coarse dust production through increased aridity and sediment availability, and/or (iv) reduced vegetation cover with lower soil stability and greater soil erosion by wind during glacial MIS 38 and MIS 22, at the onset ($\sim 1.25$ Ma) and halfway ($\sim 0.9$ Ma) through the MPT. We find that these distinctly-amplified glacial Asian climate and environmental conditions coincided with Northern Hemisphere ice sheet expansion at the onset and middle of the MPT, when expression of $\sim 100$-kyr glacial cyclicity initiated and enhanced, respectively\textsuperscript{6,8−10,13,43}. Both marine and terrestrial data suggest that glacial Northern Hemisphere ice sheets expanded substantially at the beginning of, and halfway through, the MPT. For example, various sea level reconstructions suggest notable lowstands during MIS 38 and MIS 22 relative to preceding glacial, albeit with subtle amplitude differences among reconstructions that relate to variable uncertainties in different methods\textsuperscript{6,8−10} (Fig. 4c–f). In addition, $^{26}$Al-$^{10}$Be burial dating of tills suggests that the Laurentide Ice Sheet advanced to its extreme southern limit ($\sim 40^\circ$N) at $\sim 1.3$ Ma\textsuperscript{43}. The ODP Site 887 magnetic susceptibility and Deep Sea Drilling Project (DSDP) Site 607 carbonate concentration records suggest that Northern Hemisphere ice sheets expanded and shed more ice-rafted debris into the Gulf of Alaska at $\sim 1.3$ Ma and central North Atlantic Ocean at $\sim 0.9$ Ma, respectively\textsuperscript{44,45}. We infer that the marked glacial climate intensification in Asia at $\sim 1.25$ Ma and $\sim 0.9$ Ma indicated by CLP loess coarsening may be linked to concomitant shifts to greater glacial Northern Hemisphere ice sheet expansion. Here, we subsequently use climate modelling simulations to assess whether and how Northern Hemisphere ice sheet expansion may have amplified the MPT Asian glacial conditions.

We used the Community Earth System Model (CESM 1.2) to simulate Asian climate responses to Northern Hemisphere ice sheet expansion from pre-MPT (1.6−1.3 Ma) to mid-MPT ($\sim 0.9$ Ma) glacial maximum conditions, aiming to provide a better mechanistic understanding of the observed MPT
extreme glacial events from the CLP grain size records in a global context. We note that the respective Northern Hemisphere ice sheet distributions remain poorly constrained across the MPT. To obtain reasonable configurations for the Northern Hemisphere ice sheet expansion across the MPT, our pre-MPT and mid-MPT experiments use the well-reconstructed Northern Hemisphere ice sheet distributions at 13 ka and Last Glacial Maximum (LGM, ~20 ka), respectively (Fig. 6a). We argue that these configurations are broadly realistic because sea levels$^{6,8-10}$ and benthic foraminiferal $\delta^{18}O$ values$^{31}$ are comparable for these time slices. Except for ice volume difference, we keep other boundary conditions the same in our pre-MPT and mid-MPT experiments, including well-established LGM orography, vegetation, lakes, aerosol conditions, orbital parameters, and solar constant. To better represent the early Pleistocene greenhouse gas conditions under which the MPT occurred, both experiments include CO$_2$ and CH$_4$ concentrations that are fixed to their full glacial values at ~1.5 Ma (220 ppm CO$_2$ and 450 ppb CH$_4$), as reconstructed from Antarctic ice cores$^{46}$. Note that our simulations are designed as sensitivity experiments to examine Asian climate responses to Northern Hemisphere ice sheet expansion and are not meant to reproduce exactly the full range of changing boundary conditions across the MPT.

Our simulations suggest that Northern Hemisphere glacial ice sheet expansion from the pre-MPT to mid-MPT experiments led to lowering of Asian mean annual temperature, precipitation, and net surface moisture (precipitation minus evaporation) (Fig. 6b–d), which facilitated intensification and expansion of central Asian aridity and increased dust production. Mean annual precipitation in the mid-MPT experiment decreased by ~14% in arid inland regions (60–100°E, 30–60°N) and by ~9% in East Asian monsoon regions (100–120°E, 20–40°N) relative to the pre-MPT experiment. Furthermore, ice sheet expansion strengthened Asian high-pressure cells and winter monsoon circulation (Fig. 6e–f), which enhanced winter monsoon dust transportability toward the CLP. Overall, annual dust fluxes emitted from arid regions north and east of the Tibetan Plateau increased by up to an order of magnitude from the pre-MPT to mid-MPT experiments (Fig. 6g). This was associated with a broadly doubled annual atmospheric dust loading over East Asian down-wind regions (Fig. 6h), which is comparable to the largely doubled median grain sizes of $L_{15}$ and $L_{9-1}$ relative to adjacent loess layers observed across the CLP (Figs. 2 and 4b). Dust changes are substantially larger than precipitation changes in the pre-MPT to mid-MPT experiments (Fig. 6), which is consistent with the significantly larger grain size changes compared to $\chi$ changes at ~1.25 Ma and ~0.9 Ma (Fig. 2a–b).

Our general circulation model does not include dynamic vegetation responses as vegetation is fixed. Hence, our dust inferences likely are minimum estimates because temperature and precipitation lowering across the MPT (with arid zone expansion) would have also decreased the vegetation cover$^{36,47}$, which in turn would have reduced soil stabilization, facilitating erosion and dust production and availability. Other potential dust producing processes not included in the model, such as enhanced physical weathering and rock fracturing through intensified frost wedging and/or glacial grinding under colder MPT conditions, would also produce more dust material for ablation$^{48}$. Regardless, our minimum estimates from model results strongly support the hypothesis that intensification and southeastward expansion of Asian aridity, increased coarse dust availability, and winter monsoon wind strengthening caused increased coarse dust
transport and loess coarsening across the CLP in response to Northern Hemisphere ice sheet expansion across the MPT. Our model output is broadly consistent with previous post-MPT simulations of marked ice sheet impacts on the Asian climate\textsuperscript{49–53}, although those simulations used different boundary conditions.

Consistent with the above scenario, new sandy deserts (e.g., Badain Jaran Desert, Tengger Desert) formed at \( \sim 1.2 \text{–} 0.9 \) Ma to the north of the CLP\textsuperscript{16,54}, while existing sandy deserts (e.g., Mu Us Desert) expanded southward at \( \sim 1.25 \) Ma\textsuperscript{17} (Fig. 4i). Sandy desert environments first appeared in the Hobq Desert at \( \sim 1.3 \text{–} 1.2 \) Ma, replacing preceding fluvio-lacustrine environments\textsuperscript{55}. The Tarim and Qaidam Basins also aridified from \( \sim 1.25 \) Ma onward\textsuperscript{48,56,57} (Fig. 4i). Loess coarsening and dust flux increases on the West Kunlun Shan are consistent with expanded central Asian arid regions across the MPT\textsuperscript{58}. These Asian arid regions, especially the neighbouring Badain Jaran, Tengger, Mu Us, and Hobq Deserts (see Fig. 1a for locations), provided important coarse dust sources for the CLP\textsuperscript{16}. Southeastward desert condition expansion to the west and north of the CLP together with synchronous winter monsoon wind strengthening could readily lead to loess coarsening on the CLP. The amplified expression of grain size pulses during MIS 38 and MIS 22 relative to their preceding glacial intervals suggests nonlinear responses of dust accumulation on the CLP to Northern Hemisphere ice sheet expansion (Fig. 4). The CLP grain size responses appear to have been more vigorous at the onset and middle of the MPT when a hypothesized threshold of Asian aridification and winter monsoon intensity was passed for the first and second time, allowing increased coarser particles to be transported by stronger winds. For example, a change from fluvio-lacustrine to desert environments when the first (particularly) or second threshold was passed in different Asian interior arid regions, would offer more abundant dust material to be transported to the CLP than the later sustained sandy deserts without fluvio-lacustrine processes, because fluvio-lacustrine conditions generally produce abundant fine dust that can be readily transported atmospherically by the stronger winter monsoon once water bodies dried and sediments exposed\textsuperscript{59,60}. We argue that the CLP loess coarsening at \( \sim 1.25 \) Ma and \( \sim 0.9 \) Ma was related to a combination of both winter monsoon intensity and the supply of newly erodible and deflatable material in source regions. In addition to the onset and middle of the MPT, these loess coarsening events also coincided broadly with 400-kyr eccentricity minimum nodes\textsuperscript{61} (Fig. 4h), which were associated with distinct cooling events in tropical sea surface temperature records\textsuperscript{62}. Under such eccentricity node and cooling conditions, Northern Hemisphere ice sheet expansion could have more easily driven anomalous Asian glacial climate and environment changes at \( \sim 1.25 \) Ma and \( \sim 0.9 \) Ma. It appears that the studied events across the MPT are consistent with non-linear responses that broadly exist in astronomical climate dynamics\textsuperscript{63–65}.

Synthesizing observations, land-sea correlations, and simulations, we propose that Northern Hemisphere ice sheet expansion drove large-scale amplification of Asian glacial conditions through hitherto unknown non-linear threshold-style responses of the Asian winter monsoon and aridification at the onset (\( \sim 1.25 \) Ma) and halfway (\( \sim 0.9 \) Ma) through the MPT, when expression of \( \sim 100\)-kyr glacial cyclicality initiated and enhanced, respectively. These greatly amplified regional glacial excursions were marked by a combination of intensified and expanded Asian aridity, winter monsoon strengthening, and summer
monsoon weakening, with distinct coarsening of the L$_{15}$ and L$_{9-1}$ layers across the CLP. Our combined palaeoclimate and simulation results offer a new perspective on the exceptional coarsening of the L$_{15}$ and L$_{9-1}$ loess layers in a globally significant context. Our findings also portray a systematic manifestation of the MPT across Asia in association with high-latitude Northern Hemisphere ice sheet expansion, shedding light on extreme climate variability across the MPT. The MPT reflects not only the well-known shift from predominantly ~40-kyr to ~100-kyr orbital cycles, but also contains distinct anomalies in terrestrial climate and environmental conditions.

**Methods**

Following surface outcrop removal, 1,115 and 982 fresh samples were collected from the Chaona and Luochuan sections, central CLP, from Holocene palaeosol layer S$_{1}$ (corresponding to MIS 1) to palaeosol layer S$_{22}$ (corresponding to MIS 55) at 10 cm intervals (equivalent to an averaged ~1–2 kyr time spacing). All samples were used for median grain size analyses after organic matter and carbonate removal. Grain sizes of these pretreated samples from the Chaona and Luochuan sections were measured with a Coulter LS 100Q laser diffraction particle size analyzer at the University of Nebraska-Lincoln, Nebraska, USA, and with a Malvern 2000 Laser Instrument at the Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China, respectively.

The CLP loess-palaeosol age models established using different approaches, including orbital tuning, land-sea correlation, and grain-size age models, are similar and match well with the marine benthic foraminiferal $\delta^{18}$O records$^{18,20,23,28}$. In particular, the extremely coarse loess layers L$_{15}$ and L$_{9-1}$ are consistently correlated to MIS 38 and MIS 22 in these age models$^{18,23,28}$. Based on the identified same correlations of loess and palaeosol layers to glacial and interglacial periods$^{18,20,23,28}$, we established the CLP loess-palaeosol chronology by correlating Luochuan and Chaona median grain size and $\chi$ records to the benthic foraminiferal $\delta^{18}$O record$^{32}$ within the magnetostratigraphic and pedostratigraphic age frame, including ages of palaeosol S$_{22}$ (MIS 55–53), the bottom (1.075 Ma) and top (0.991 Ma) of the Jaramillo subchron$^{31}$, Matuyama–Brunhes boundary (0.780 Ma)$^{31}$, and palaeosol S$_{0}$ (Holocene, MIS 1)$^{19}$ (Supplementary Fig. 1). Other CLP loess-palaeosol sections, including Lingtai$^{18,23}$, Jingchuan$^{18,35}$, Baicaoyuan$^{33}$, Zhaojiachuan$^{23}$, and Lantian$^{36}$, were synchronized to this chronology by median grain size or $\chi$ correlations. After synchronization, we used the interpolating function in the Acycle software$^{66}$ to conservatively resample the grain size and $\chi$ records at 0.5-kyr intervals to obtain evenly spaced data series, which were further averaged to establish median grain size and $\chi$ stacks. The $\chi$, median grain size, and LR04 benthic foraminiferal $\delta^{18}$O stacks$^{31}$ were subjected to spectral analysis to evaluate the robustness of their potential orbital signature. Evolutionary power spectra were calculated using the Acycle software$^{66}$ with a 320-kyr sliding window and ~3-kyr step. To improve expression of the orbital transition across the MPT from ~40-kyr to ~100-kyr cycles in the $\chi$ and median grain size records, their longer trends were removed with a low-band-pass filter; the residual records were used for evolutionary power spectral analysis.
The Community Earth System Model (CESM 1.2) was used to test the sensitivity and underlying Asian climate response dynamics to Northern Hemisphere ice sheet expansion across the MPT. The CESM consists of coupled dynamic atmosphere, ocean, land, sea-ice, and land-ice components. We used the Community Atmosphere Model (CAM), Community Land Model (CLM), Parallel Ocean Program (POP), Community Sea-Ice Component (CICE), and Coupler modules in the CESM. The CAM has a Bulk Aerosol Model (BAM) parameterization of dust emission, transport, and deposition, which is suggested to be useful for simulating dust emission flux and loading in Asia. The atmosphere has 26 vertical layers and ~ 0.9° (latitude) × 1.25° (longitude) horizontal resolution. The land model has 15 soil layers and the same horizontal resolution as the atmosphere. Ocean and sea-ice components have 60 vertical layers with 0.5° horizontal resolution. To evaluate Asian climate responses to MPT Northern Hemisphere ice sheet expansion, we performed two numerical experiments: pre-MPT and mid-MPT (see main text for boundary condition details). Both experiments were integrated for 150 model years from the equilibrated LGM initial conditions based on the Palaeoclimate Modelling Intercomparison Project (PMIP3) LGM experiment (http://pmip3.lsce.ipsl.fr). Climatological means of the last 50 model years were used here.

Declarations

Data availability. All measured proxy data presented here are attached in the Supplementary Dataset and will also be available in the East Asian Palaeoenvironmental Science Database (http://palaeodata.ieecas.cn/index.aspx).

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Author Contributions

H.A. designed the study and compiled the data. Y.G.S, Y.M.H., and X.K.Q. conducted the field work. X.Z.L. conducted the simulations. Y.G.S and Y.M.H carried out the laboratory analysis. X.X.L. undertook the spectral analysis. All authors contributed to data analysis, interpretation, and/or discussion. H.A. and X.X.L. made the figures. H. A. wrote the manuscript, with contributions from all other authors.

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Figures

Figure 1

Site location map. (a) Map of Asian dust sources (Tibetan Plateau, Gobi and other deserts, and wind eroded land) and aeolian loess deposits in North China16. (b) Map of the CLP with the locations of our studied Chaona and Luochuan sections (red stars), and other loess-palaeosol sections (black solid circles) discussed. The Yellow River system of North China is indicated by the dark blue line.

Figure 2

Grain size variations of loess-palaeosol sequences across the CLP. Median grain size records from the (a) Luochuan (this study), (b) Chaona (this study), (c) Lingtai18, (d) Jingchuan18, and (e) Baicaoyuan33 sections. (f) CLP median grain size stack. (g) LR04 marine benthic δ^{18}O record31. L-numbers refer to consecutive loess horizons counting back from the present-day. Pink bars indicate the correlation of median grain size of marker loess layers (L_{15} and L_{9-1}) to glacial stages (MIS 38 and MIS 22).

Figure 3

Magnetic susceptibility variations of loess-palaeosol sequences across the CLP. Magnetic susceptibility (χ) records from the (a) Luochuan32, (b) Chaona27, (c) Jingchuan35, (d) Zhaojiachuan23, (e) Lantian36, and (f) Lingtai23 loess-palaeosol sections across the CLP. (g) CLP χ stack (this study). (h) LR04 marine benthic δ^{18}O record31. S-numbers refer to consecutive palaeosol horizons counting back from the present-day. Pink bars indicate the correlation of χ of marker loess layers (L_{15} and L_{9-1}) to glacial stages (MIS 38 and MIS 22).
Figure 4

Terrestrial and global climate variability on glacial-interglacial timescales across the MPT. Our newly established CLP (a) χ and (b) composite median grain size stacks. S-numbers and L-numbers refer to consecutive palaeosol and loess horizons counting back from the present-day, respectively. Sea level reconstructions from the (c) Mediterranean Sea record8, (d) Pacific benthic foraminiferal δ18O and Mg/Ca records10, (e) seawater δ18O from ODP site 1123, South Pacific Ocean9, and (f) global benthic foraminiferal δ18O stack. (g) LR04 benthic foraminiferal δ18O record31. Numbers refer to Marine Isotope Stages, counting back from the present-day. (h) Eccentricity and its filtered 400-kyr component. (i) Enhanced Asian aridification, new desert formation, and desert expansion from ~1.25 Ma onward inferred from geological records16,17,48,54,56,57. Pink bars indicate the correlation of coarse marker loess layers (L15 and L9,1) to glacial stages (MIS 38 and MIS 22).

Figure 5

Orbital-scale climate variability across the MPT. Spectral evolution of the (a) CLP χ stack, (b) CLP median grain size stack, and (c) LR04 benthic foraminiferal δ18O record31.

Figure 6

Simulated Asian climate and atmospheric circulation responses to ice volume increase across the MPT. (a) Northern Hemisphere ice sheet distribution used in the pre-MPT (upper) and mid-MPT (lower) simulations. The yellow dot represents the CLP. Simulated changes (mid-MPT minus pre-MPT) in (b) annual temperature, (c) annual precipitation, (d) annual net moisture (precipitation minus evaporation), (e) Asian high-pressure cell during winter, and (f) winter monsoon (700 hPa winds) due to ice sheet expansion from the pre-MPT to the mid-MPT experiments. Mid-MPT to pre-MPT ratios of atmospheric (g) annual dust emission flux and (h) annual dust loading. Solid green contours in b–h denote the 3,000 m topographic contour, which includes the Tibetan Plateau. Red stars represent the Chaona and Luochuan loess-palaeosol sections. Small red dots in b–h denote regions with statistical significance above the 95% confidence level (Student’s t-test). Winter in the model is represented by December to February.

Supplementary Files
This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarydata.xlsx
- SupplementaryInformation.pdf