ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL103633

Mongolian Dust Activity Over the Last 25 Kyr Predominantly Driven by the East Asian Winter Monsoon: Insights From the Geochemistry of Lake Tuofengling Sediments

Wenfang Zhang[1], Enlou Zhang[1], Enfeng Liu[2], Jordan T. Abell[3], Weiwei Sun[1], Zhenyu Ni[1], Rong Chen[1], Yue Cai[4], and Xianqiang Meng[1]

[1]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China, [2]College of Geography and Environment, Shandong Normal University, Ji'nan, China, [3]Department of Geosciences, University of Arizona, Tucson, AZ, USA, [4]State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology and Center for Excellence in Life and Paleoenvironment, Chinese Academy of Sciences, Nanjing, China

Key Points:

- Geochemical evidence suggests that the Mongolian Plateau (MP) is the main source of dust for Lake Tuofengling (TFL)
- The East Asian Winter Monsoon (EAWM) is likely the dominant carrier of aeolian dust from the MP to TFL
- Dust flux and EAWM variability could be driven by a combination of changes in ice volume and Atlantic Ocean circulation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

E. Zhang,
elzhang@niglas.ac.cn

Citation:

Zhang, W., Zhang, E., Liu, E., Abell, J. T., Sun, W., Ni, Z., et al. (2023). Mongolian dust activity over the last 25 Kyr predominantly driven by the East Asian Winter Monsoon: Insights from the geochemistry of Lake Tuofengling sediments. *Geophysical Research Letters*, *50*, e2023GL103633. https://doi.org/10.1029/2023GL103633

Received 10 MAR 2023
Accepted 9 JUN 2023

Author Contributions:

Conceptualization: Wenfang Zhang, Enlou Zhang, Xianqiang Meng
Data curation: Wenfang Zhang, Enlou Zhang, Enfeng Liu, Yue Cai, Xianqiang Meng
Funding acquisition: Enlou Zhang
Methodology: Wenfang Zhang, Enlou Zhang
Project Administration: Enlou Zhang
Resources: Enlou Zhang, Enfeng Liu, Weiwei Sun, Zhenyu Ni, Rong Chen
Supervision: Enlou Zhang

Abstract

Dust deposition in northeastern Asia since the Last Glacial Maximum has previously been studied using a variety of archives. However, the mechanisms driving variability in dust are less well constrained. Here, we present records of the Nd-Sr isotope and major element composition of sediments from Lake Tuofengling, a crater lake located in northeastern China, over the past ~25 thousand years. The results indicate that the lithogenic fractions of the sediments are a mixture between aeolian dust and local volcanic detritus. Our provenance data suggest that the aeolian dust component is predominantly from the Mongolia Plateau, likely carried by the East Asian Winter Monsoon. Our isotope and calculated dust flux records exhibit similar changing patterns to proxies of global ice volume and the strength of Atlantic meridional overturning circulation, potentially implicating ice sheets and ocean circulation as the dominant drivers of the East Asian Winter Monsoon over this time interval.

Plain Language Summary

Dust storms occur frequently throughout Central and East Asia today. Several driving factors, particularly related to the East Asian Summer Monsoon, the East Asian Winter Monsoon (EAWM), and the westerlies, can influence dust production and transport in these regions, both in the modern and during the past. Uncovering the dominant factor(s) can assist in furthering our understanding of atmospheric circulation over Asia during climates both similar and different from today. Here, we collected sediments from a crater lake (Lake Tuofengling (TFL)) located in northeastern Asia and reconstructed dust inputs over the past 25 thousand years. We found that the dust delivered to TFL sediments is mainly sourced from the Mongolian Plateau associated with transport via winds related to the EAWM. Further in-depth analysis indicates that shifts in ice volume and Atlantic Ocean circulation may be important drivers for the EAWM, at least over the past 25 thousand years.

1. Introduction

The regional climate of East Asia is influenced by several atmospheric circulation systems, including the mid-latitude westerly winds, the East Asian Winter Monsoon (EAWM), and the East Asian Summer Monsoon (EASM). Changes in the westerlies and the Siberian-Mongolian High, the latter of which influences low-level winds associated with the EAWM, have previously been considered as mechanisms linking abrupt climate changes in the North Atlantic and East Asia, at least over the last ~60 thousand years (Kyr) (e.g., Kang et al., 2022; Sun et al., 2012; Zheng et al., 2017). For example, it has previously been suggested that shifts in Atlantic Meridional Overturning Circulation (AMOC) at least partially controlled atmospheric circulation over East Asia during the late Pleistocene (Vandenberghe et al., 2006). As such, numerous studies have attempted to characterize the timing and magnitude of shifts in these wind systems over the last several tens of thousands of years using various archives in Asia (e.g., Kang et al., 2022; Safaierad et al., 2020; Sun et al., 2012).

Wind is an important driver of dust emissions and transport, and as such records of dust activity in East Asia can provide insight into changes in the regional monsoonal systems and the westerlies. The EAWM (Kang et al., 2015, 2022), EASM (Yang & Ding, 2008) and Northern Hemisphere westerlies (Y. Li et al., 2016) have all previously been invoked to explain patterns of East Asian dust deposition and grain size during the late

Validation: Wenfang Zhang, Enlou Zhang
Visualization: Wenfang Zhang
Writing – original draft: Wenfang Zhang
Writing – review & editing: Wenfang Zhang, Enlou Zhang, Jordan T. Abell, Yue Cai, Xianqiang Meng

Pleistocene. On a broader scale, some existing records show correspondence between changes in AMOC, Asian atmospheric circulation, and dust deposition on the Chinese Loess Plateau (CLP) and in northeast Iran (Kang et al., 2022; Safaierad et al., 2020; Sun et al., 2012). As a result, reconstructions of Asian dust, specifically from regions impacted by monsoon systems and the westerlies, may provide insight into changing characteristics of the atmospheric conditions as well as their linkage to North Atlantic climate. One such area is northeastern China, which lies at the northernmost margin of the EASM and is influenced by the EAWM and the westerlies as well. Considering the location, archives containing dust from northeastern China could provide crucial constraints on the relationship between the climate of East Asia and the broader Earth System.

Peatland and lake sediments from northeastern China have been used to trace the source of dust and its temporal variability in relation to external forcing(s) (Fialkiewicz-Koziel et al., 2022; Pratte et al., 2019; Zaarur et al., 2020; Zhou et al., 2023; Zhu et al., 2013). A 14 Kyr-long dust flux record from the Hani peatland displays a sharp increase in dust deposition during the late Holocene compared to the middle and early Holocene, which the authors suggest implies modulation by variations in the EASM (Pratte et al., 2019). A low-resolution record of Nd and Sr isotopes from Lake Sihailongwan indicates that changes in the isotope composition of the sediments could be related to either the El Nino Southern Oscillation, or to delays in the onset of EASM precipitation (Zaarur et al., 2020). Additionally, rare earth element (REE) ratios of Motianling peatland sediments in Aershan in the Great Hinggan Mountains resemble dust samples from the Gobi and northern Chinese deserts, pointing to transport via the westerlies and EAWM-related winds (Fialkiewicz-Koziel et al., 2022). Finally, Nd and Sr isotope measurements from Lake Tianchi indicate that the Hulun Buir Sandy Land (HBSL) is the main source of dust to the area during the Holocene, and the reconstructed dust flux shows an overall decreasing trend of aridity from the early to mid-Holocene (Zhou et al., 2023). While the aforementioned datasets have attempted to provide constraints on the drivers of terrestrial inputs to various archives, the response of dust activity to changes in EAWM intensity, and potentially North Atlantic climate, from a northeastern China perspective is still not well studied, ultimately hindering our understanding of Asian dust dynamics since the last glacial period. Considering the results of these previous studies, remote impacts of the North Atlantic climate change on atmospheric circulation over East Asia, and in turn regional dust variability, can be assessed using proxies for dust provenance.

Here, we provide a new record of major element and Nd-Sr isotope compositions from a crater lake in northeastern China spanning the past ~25 Kyr. Lake Tuofengling (TFL) is situated at the northern limit of the EASM and downwind of the EAWM, making it an ideal archive to record dust variations impacted by these monsoonal systems. We propose that the observed Nd and Sr isotope and dust flux variations reflect changes in the strength of the EAWM in northeastern China. The correspondence between our dust flux reconstruction and broader shifts in the climate system (i.e., ice sheets and AMOC) provides evidence for synchronous changes in dust storm activity and ice volume as well as North Atlantic climate over the past 25 Kyr BP.

2. Methods

2.1. Sediment Archive

Lake TFL (47°27′39″N, 120°38′22″E, 1275 m a.s.l.) is located in the Arxan-Halaha volcanic field in the central part of the Great Khingan Mountain Range, Yiershi Town, Arxan City, Inner Mongolia, northeastern China (Figure 1a). The crater lake is a small, hydrologically closed lake formed during the late Pleistocene. It sits atop a scoria cone composed of scoriaceous pyroclastic deposits (Ho et al., 2013; Y. Zhao & Fan, 2012).

Lake TFL is situated at the northern limit of the EASM and downwind of low-level winds associated with the EAWM (Figure 1b). The presence of large subtropical deserts in and around Central and East Asia, capable of releasing substantial amounts of dust particles into the atmosphere, make East Asian sedimentary sequences potential records of regional atmospheric circulation systems.

A 12.55 m-long sediment core was retrieved in June 2017 from the center of Lake TFL at a water depth of about 32 m using a 55 mm diameter percussion corer (Figure 1c). The upper 6.2 m of the core is black in color, with substantial organic material. A gradual color transition occurs from black to gray-yellow between 6.2 and 7.5 m. The section below 7.5 m is gray-yellow in color. The core was subsampled continuously at 1 cm intervals. The sediment subsamples were freeze-dried and then weighed for the determination of dry bulk density (Text S1 in Supporting Information S1).

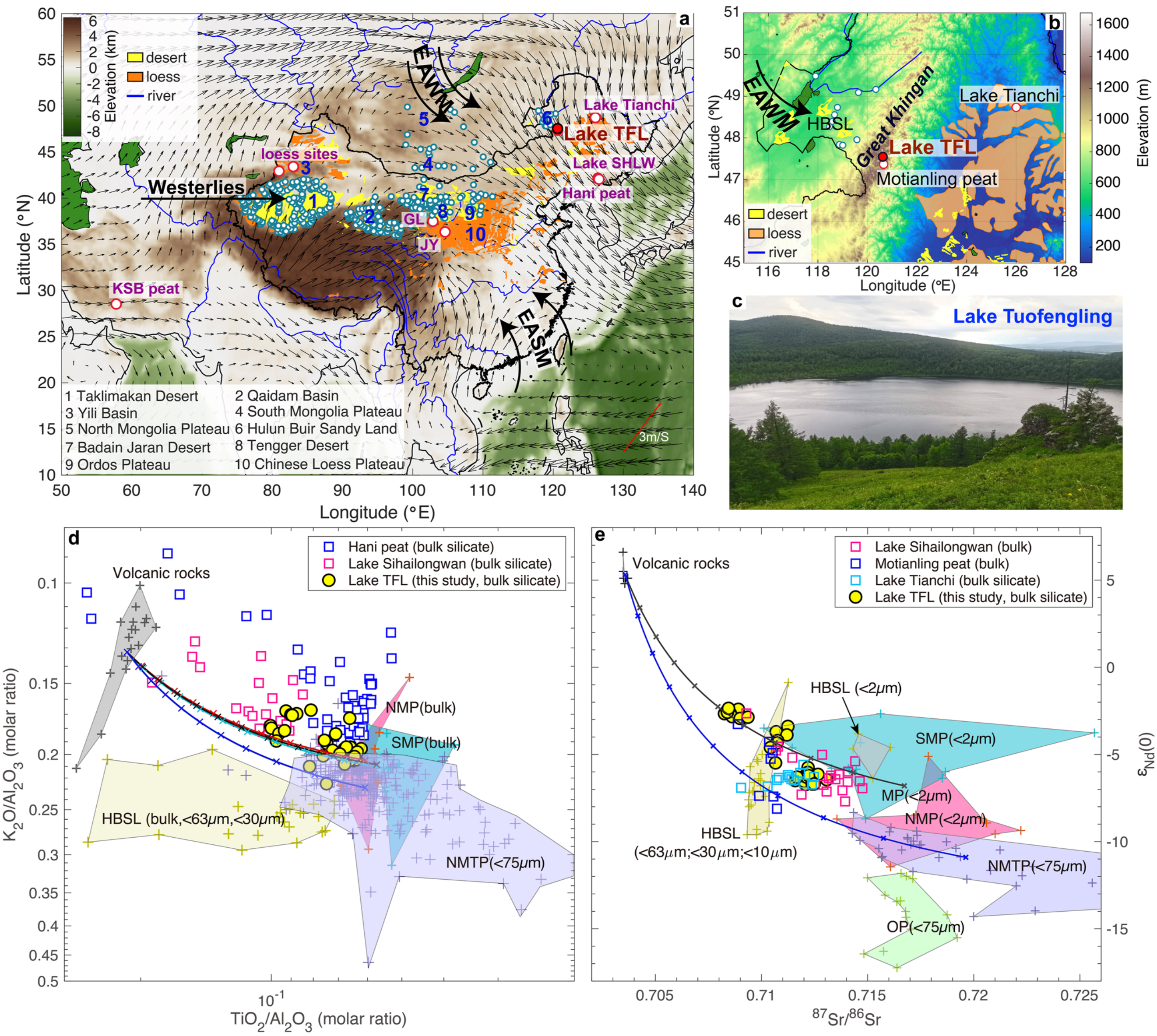

Figure 1. Location of Lake Tuofengling (TFL) as well as sample locations cited in this study as well as dust source discrimination of Lake TFL sediments using major element geochemistry and Nd-Sr isotopes. Arrows indicate monthly 850 hPa winds for January averaged from 1948 to 2014 (data are taken from www.esrl.noaa.gov/psd/) (a). Red solid dots denote Lake TFL. The other dots show the locations cited in this study. Lake SHL, Lake Sihailongwan; GL, Gulang loess; JY, Jingyuan loess; EAWM, East Asian Winter Monsoon; EASM, East Asian Summer Monsoon. (b) Topographic map showing Lake TFL and its adjacent region. (c) Lake TFL and its catchment. (d) Plot of K_2O/Al_2O_3 versus TiO_2/Al_2O_3 molar ratios for the samples from Lake TFL in northeastern China and Hani peat (Pratte et al., 2019), Lake Sihailongwan (Zaarur et al., 2020), the Hulun Buir Sandy Land (HBSL) (Xie et al., 2018), North Mongolian Plateau (NMP) (W. Zhao, 2015), North Margin of Tibetan Plateau (NMTP) (Lin et al., 2020), Southern Mongolian Plateau (SMP) (W. Zhao, 2015) and the local volcanic rocks (Ho et al., 2013; Y. Zhao & Fan, 2012). The red, green, black and black lines indicate the end member mixing lines between local volcanic rocks and remote dust from the NMP, the SMP, the average Mongolian Plateau, and the NMTP, respectively, with 10% increments denoted. The element concentrations of potential source areas are provided in the Table S2 in Supporting Information S1. (e) Comparisons of $\varepsilon_{Nd}(0)$ and $^{87}Sr/^{86}Sr$ composition of Lake TFL samples with regional lake and peatland records as well as potential source regions. Potential sources of Asian dust include the deserts from the NMTP (<75 μm; Taklamakan desert, Qaidam basin, Badain Jaran and Tengger desert (Chen et al., 2007; G. Li et al., 2009)); Ordos Plateau (OP), including Hobq and Mu Us (Chen et al., 2007; G. Li et al., 2009); NMP (W. Zhao et al., 2015); SMP (Biscaye et al., 1997; Bory et al., 2003; W. Zhao et al., 2015); HBSL (Chen et al., 2007; Xie et al., 2018). Regional records include Lake Sihailongwan (Zaarur et al., 2020), Motianling peatland (Fialkiewicz-Koziel et al., 2022) and Lake Tianchi (Zhou et al., 2023). The black and blue lines indicate the endmember mixing lines between local volcanic rocks (Ho et al., 2013; Y. Zhao & Fan, 2012) and remote dust from the MP and NMTP, respectively, with 10% increments denoted. Local volcanic rocks, MP and NMTP endmember isotopic compositions and element concentrations are provided in the Table S3 in Supporting Information S1.

2.2. Chronology

Eleven freeze-dried samples (five terrestrial plant material samples, two insects, three bulk sediment samples, and one organic sediment sample) were taken from the core for radiocarbon dating via accelerator mass spectrometry (AMS) at the Beta Analytic Laboratory (USA). The results were converted to calendar age based on IntCal13 (Reimer et al., 2013). Ages are expressed in years before present (BP), where "present" is defined as calendar year 1950. The Bayesian age model was produced using the 11 AMS ^{14}C dates and the "BACON" program following the method of Blaauw et al. (2018) with the "R" software (R Development Core Team, 2010). The age model for Lake TFL demonstrates that the core spans the past ~25,000 calendar years. All radiocarbon data are listed in Table S1 in Supporting Information S1 and shown in Figure S1 in Supporting Information S1.

2.3. Elemental Geochemistry and Nd-Sr Isotopes

A total of 34 bulk samples were processed for elemental geochemistry and Nd-Sr isotopes. Samples were freeze-dried and powdered using an agate mortar and pestle. Organic matter and carbonate in the samples were removed using 10% H_2O_2 and 10% HCl, respectively. About 200 mg of decarbonated dry lake sediments powder was placed in Teflon® vessels (50 mL) along with 3 mL of concentrated HNO_3 and 1 mL of concentrated HF. The vessels with the sample powders were heated in an oven for 48 hr at 180°C in an Acid Digestion Bomb. After cooling, the solutions were evaporated to near dryness on a hotplate. The remaining solutions were then diluted with 2% HNO_3 and transferred to centrifuge tubes. A portion of the digested samples were run for major elements. Specifically, selected major element (Na, Mg, Al, K, Ca, Fe, Ti, and Mn) measurements were completed on an Agilent Technologies 7500ce Q-ICP-AES at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS). The remaining fraction of the dissolved samples digested was used for Nd-Sr isotope analysis. Chemical separations were performed in a Class 100 clean lab. Nd-Sr isotopes were measured using a Neptune Plus MC-ICP-MS at the State Key Laboratory of Palaeobiology and Stratigraphy (SKLPS) in Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (NIGPAS). For Sr isotopes, in-run mass bias was corrected by normalizing measured isotopes to $^{86}Sr/^{88}Sr = 0.1194$. In-run mass bias for Nd isotopes was corrected by normalizing measured isotopes to $^{146}Nd/^{144}Nd = 0.7219$. Nd isotope ratios are reported as $\varepsilon_{Nd}(0)$, the deviation in parts per 10,000 from the "chondritic uniform reservoir" value of $^{143}Nd/^{144}Nd = 0.512638$ (Jacobsen & Wasserburg, 1980). Detailed Nd-Sr isotopes measurements procedures are provided in Text S2 in Supporting Information S1.

3. Results and Discussion

The upper continental crust (UCC)-normalized (Rudnick & Gao, 2014) concentrations of major elements in the Lake TFL sediments exhibit lower values (except for K_2O and P_2O_5) than the local mafic alkali olivine basalt and olivine tholeiite (Figure S2 in Supporting Information S1) (Ho et al., 2013; Y. Zhao & Fan, 2012). In fact, the deviation of UCC-normalized patterns of Lake TFL major element concentrations from the local parent material suggests mixing between the local basalts (Ho et al., 2013; Y. Zhao & Fan, 2012) and another more distally-derived component (Figure S2 in Supporting Information S1). The Al_2O_3/TiO_2 ratio of TFL Lake sediments ranges from 12.7 to 19.4, within the range of 8 and 21, suggesting a mix between local mafic rocks and material more felsic in composition (Girty et al., 1996). Because the lake has no inlet or outlet, the felsic material is most likely windblown aeolian dust derived from semi-arid and arid regions upwind. The North Mongolian Plateau (NMP), South Mongolian Plateau (SMP), and HBSL are the most likely potential source regions, as the dust emitted from these two regions could be transported to Lake TFL via the EAWM (Chen et al., 2007; W. Zhao et al., 2015) (Figure 1b). TiO_2/Al_2O_3 and K_2O/Al_2O_3 molar ratios are compared to aid in identifying the source regions of material deposited in Lake TFL sediments. Using the TiO_2/Al_2O_3 and K_2O/Al_2O_3 molar ratios of these potential source areas and our samples, we find that the lithogenic fractions of Lake TFL could distribute along mixing lines between the NMP endmember and local volcanic rocks as well as the SMP and local volcanic rock, with the two Mongolian Plateau (MP) sources dominating in each case (Figure 1d). For simplicity and completeness, we consider the NMP and SMP as a combined MP source for the remainder of our analysis and discussion.

To test our hypothesis for the provenance of the felsic fraction of Lake TFL sediments based on major element ratios, we use Nd and Sr isotopes, which have been shown to be effective indicators of sediment provenance (Chen et al., 2007; Grousset & Biscaye, 2005). The Nd and Sr isotope records varied markedly over the past

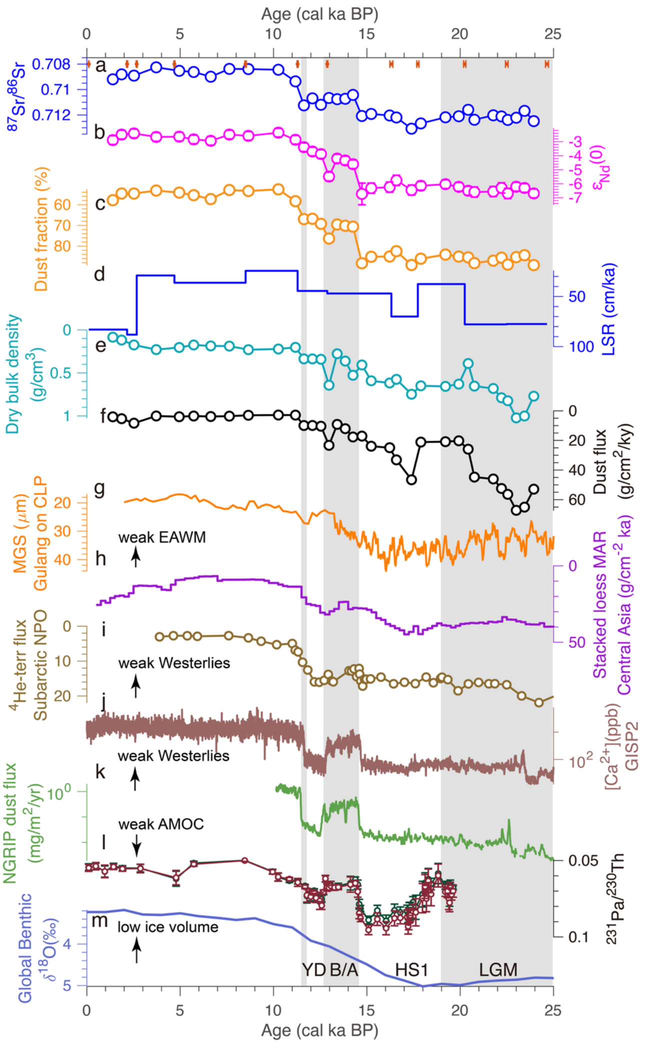

Figure 2. East Asian and global climate records from LGM to present. (a) Lake TFL $^{87}Sr/^{86}Sr$ ratios; (b) Lake TFL $\varepsilon_{Nd}(0)$ values; (c) Dust fraction for Lake TFL sediments calculated using Nd-Sr isotope endmember modeling approach; (d) Linear sedimentation rate of Lake TFL; (e) Dry bulk density for Lake TFL sediments; (f) Lake TFL dust flux based on calculated dust fraction multiplied by the age model-derived linear sedimentation rate and dry bulk density; (g) grain-size record from the Chinese Loess Plateau (CLP) (Sun et al., 2012); (h) stacked mass accumulation rate (MAR) record in the Yili Basin, Central Asia (CA) (Kang et al., 2022); (i) ^{4}He-terr flux record at site SO202-7-6 in western Subarctic North Pacific Ocean (Serno et al., 2015); (j) Ca^{2+} concentration from Greenland Ice Sheet Project (GISP) 2 ice cores as a proxy for dust input in Greenland (Mayewski et al., 1997); (k) Dust fluxes for the North Greendland Ice Core Project (NGRIP) ice core using the published dust concentration data, reconstructed ice accumulation rates for the NGRIP ice core (Ruth et al., 2007), and the density of ice (917 kg/m^3) (Serno et al., 2015); (l) $^{231}Pa/^{230}Th$ ratios from the subtropical North Atlantic (McManus et al., 2004) as a proxy for the strength of AMOC; (m) Global benthic $\delta^{18}O$ as a proxy for global ice volume and deep water temperature (Lisiecki & Raymo, 2005). Eleven AMS ^{14}C dates and errors (2σ error bars at top) are also plotted. YD, Younger Dryas stadial; B/A, Bølling–Allerød interstadial; HS1, Heinrich Stadial 1; LGM, Last Glacial Maximum; TFL, Lake Tuofengling.

~25 Kyr BP (Figures 1e, 2a and 2b). The $\varepsilon_{Nd}(0)$ values of our samples range between −6.72 and −2.35, while the $^{87}Sr/^{86}Sr$ ratios range between 0.708256 and 0.713075 (Figure 1e; Supplementary Dataset). $\varepsilon_{Nd}(0)$ values and $^{87}Sr/^{86}Sr$ ratios of Lake TFL sediments exhibit negative correlations. Additionally, the Nd and Sr isotope compositions of the sediments are distinctly different from those of the basaltic rocks surrounding the lake (Ho et al., 2013; Y. Zhao & Fan, 2012). Specifically, $\varepsilon_{Nd}(0)$ values are lower, while $^{87}Sr/^{86}Sr$ ratios are much higher.

The negative correlation between the Nd and Sr isotope composition of the silicate fractions of Lake TFL sediments also suggests binary mixing between the local mafic bedrocks and a dust with more evolved composition that likely originates from upwind desert areas (Figure 1e). A large database of Nd and Sr isotopes of detrital sediment from various size fractions (<63, <10, and <2 μm) exists for both the HBSL and the Mongolian Gobi desert (i.e., the MP) (Chen et al., 2007; G. Li et al., 2009; Xie et al., 2018; W. Zhao et al., 2015). The local Halaha volcanic rocks are characterized by high $\varepsilon_{Nd}(0)$ values and less radiogenic $^{87}Sr/^{86}Sr$ ratios (Ho et al., 2013; Y. Zhao & Fan, 2012). Aeolian dust transported from the Mongolian Gobi desert is also a potential source with low $\varepsilon_{Nd}(0)$ values and radiogenic $^{87}Sr/^{86}Sr$ ratios (Chen et al., 2007; G. Li et al., 2009; Xie et al., 2018; W. Zhao et al., 2015). Binary mixing between local volcanic debris and remote aeolian dust from the Mongolian Gobi desert (here we use the average isotope values of the SMP and NMP, but not the HBSL) can account for the negative Nd-Sr isotope correlation of Lake TFL sediments (Figure 1e). This finding is consistent with our interpretations of the TiO_2/Al_2O_3 and K_2O/Al_2O_3 molar ratios, which can also be used to distinguish sediment source areas (Hao et al., 2010; Peng et al., 2016). Based on these observations, it is clear that the felsic end member of the Lake TFL sediments is derived mainly from arid, dust-producing regions in the MP rather than the HBSL (Figures 1d and 1e).

We note that the Northern Margin of the Tibetan Plateau (NMTP) could also be a possible dust source region for Lake TFL sediments. However, endmember modeling of both major elements and Nd and Sr isotopes shows only a minor overlap between Lake TFL sediments and mixing of local volcanics and NMTP material (Figure 1e), indicating that the NMTP is not the main source region for non-local terrigenous material. Additionally, Lake TFL is located far to the north of the NMTP sources, and not within the typical transport pathway of dust sourced from central China today (Tsai et al., 2008), further ruling out the potential of the NMTP as the dominant source region of dust in TFL sediments. In summary, the Nd-Sr isotope composition and elemental geochemistry of Lake TFL deposits in northeastern China suggest that the deserts in the MP are the main source of dust in Lake TFL.

Our ~25 Kyr-long, millennial-scale Nd and Sr isotope record from Lake TFL is an important contribution to our understanding of dust provenance and atmospheric dynamics of East Asia, as there is a paucity of Nd-Sr isotope data from northern China that span the period from the Last Glacial Maximum (LGM) to present. The nearest Nd-Sr isotope record, which only captures the last 135 years, is from the Motianling peatland, a few tens of kilometers away from Lake TFL. The authors of this study found that detrital material in the peat were sourced from northern China and Mongolia (Fialkiewicz-Koziel et al., 2022), similar to our results for the last ~25 Kyr. However, their data also showed that the HBSL could be an additional potential source region of dust found in the Motianling peat (Figure 1e). While this may seem to contradict our results, one confounding factor when applying the findings of Fialkiewicz-Koziel et al. (2022) to paleo-dust records on longer timescales is that human activity and/or recent vegetation change in the HBSL could provide a mechanism to explain emitted dust transported to the Motianling peatland in the recent past (Liang et al., 2022). For completeness, we note that the absence of HBSL dust in Lake TFL sediments could also be attributed to the low resolution (~0.74 Kyr between samples on average) of the record from Lake TFL, which may not record extreme dust events in the HBSL as described in Fialkiewicz-Koziel et al. (2022).

Other regional records are from Lake Sihailongwan, the Hani peatland, and Lake Tianchi (Figures 1a and 1b). The elemental and Nd-Sr isotopic compositions of Lake Sihailongwan sediments spanning the last 80 Kyr suggest that lake sediments are dominated by aeolian input from the arid regions of northern China, with little contribution of local volcanic material (Zaarur et al., 2020). However, source identifications based on Nd and Sr isotopes from the sediments of Lake Sihailongwan seem more complicated than those of Lake TFL. This could arise because these records may be affected by remote dust delivered via upper-level westerlies from the deserts of western China (Zaarur et al., 2020). By contrast, Lake TFL, located farther to the north, is predominantly in the pathway of dust transportation via the EAWM, bringing detrital material from more northern areas (i.e., the MP) than that received by Lake Sihailongwan and the Hani peat (Figure 1), although this remains a speculation. Nd-Sr isotopes and elemental ratios of the clastic materials in Holocene sediments from Lake Tianchi are posited to be mainly sourced from the HBSL, even though Nd-Sr isotopes exhibit similar compositions with that of Lake TFL (Zhou et al., 2023) (Figure 1e). Taken together, our results combined with existing datasets indicate that the Lake TFL geochemical data may provide a unique record of MP-derived dust, and in turn could be used to reconstruct variations in regional atmospheric circulation.

To directly constrain changes in dust input, we use a mixing model based on the combined Sr and Nd isotopes between the MP and local volcanic endmembers to calculate a dust fraction spanning the last ~25 Kyr (Figure 1e; Text S3 in Supporting Information S1). Using this dust fraction record, age model-derived linear sedimentation rates, and dry bulk density (Text S1 in Supporting Information S1), we then calculate dust fluxes for Lake TFL. Prominent features of our dust flux record are (a) a markedly high dust input during the early LGM and Heinrich Stadial 1 (HS1), (b) a decline in dust between ~21–18 Kyr BP, (c) a decrease during the interval of ~16–11 thousand years ago (ka), and (d) relatively constant and low dust supply during the Holocene (Figure 2f). These changes generally correspond to other dust records from East Asia (Figures 2g and 2h) that are proposed to be impacted predominantly by the EAWM (Sun et al., 2012). The two isotope records show similar variability to the dust fluxes (i.e., high in the early LGM and low in the Holocene), except for the change during HS1, where dust fluxes seem to be driven by an increase in sedimentation rate at this time. The slight inconsistency observed between the Nd and Sr isotope records, especially during the deglacial period (~14–11.7 ka), might be attributed to effect of grain size on the Sr isotopes, with fine fractions having more radiogenic $^{87}Sr/^{86}Sr$ (e.g., Chen et al., 2007). Regardless, the major features of the isotope records (and the mixing curves produced for identified endmembers) for Lake TFL sediments indicates that source change may have been the dominant factor controlling the Nd and Sr isotopic compositions (and in turn dust fractions), with grain size possibly exerting only a minor effect (Figures 1e, 2a, and 2b). Overall, we find that the observed variability in dust deposition during these specific intervals, along with our dust provenance data and archive location, imply a link to shifts in the low-level winds related to the EAWM over the last ~25 Kyr BP. For completeness, we note that the westerlies could also play a role in bringing material to Lake TFL. However, considering the dust source identified here and its relation to the deposition site, the westerlies (particularly the near-surface component) are likely not the dominant transport mechanism for dust transport to Lake TFL, particularly during colder climate when the westerly jet remains south of the Tibetan Plateau for much of the year (Chiang et al., 2015). Regardless, while we focus on the connection between broader climate change in the Earth System and the EAWM for the remainder of our interpretations, there is a similar pattern of variability between the EAWM and the westerlies over East Asia for the late Pleistocene (e.g., Vandenberghe et al., 2006), implying our interpretations regarding distal forcing mechanisms are independent of the dominance of a particular feature of regional atmospheric circulation.

With confidence in the primary driver of dust deposition in Lake TFL for at least the last ~25 Kyr BP, we now turn to assessing its relationship to climatic changes during the late Pleistocene and Holocene. A comparison of the Lake TFL sediment record with an aeolian dust flux record from the subarctic North Pacific Ocean (Serno et al., 2015) as well as Ca^{2+} concentrations and dust flux from Greenland (Mayewski et al., 1997; Ruth et al., 2007) demonstrates that the dust variations in all three locations are relatively similar since at least ~25 ka BP, but with notable differences (Figures 2i–2k; Figures S3 and S4 in Supporting Information S1). Some millennial-scale features (e.g., the Younger Dryas and Bølling-Allerød) are absent in our record, which may be due to the resolution of our age model and/or sampling interval (~0.74 Kyr) across these intervals. However, our new record contains an increase in dust during HS1, which is not observed in the other records mentioned here. Additionally, while the North Pacific and Greenland records display an abrupt change in dust inputs across the deglaciation, the Lake TFL dust flux reconstruction seems to show a gradual change from the end of the LGM to the beginning of the Holocene. These discrepancies may point to multiple mechanisms driving EAWM variations (and regional dust dynamics) during the last ~25 Kyr BP that are not reflected in more distal dust archives. We now turn to evaluating previously proposed connections between East Asian atmospheric circulation and Northern Hemisphere climate in the context of our geochemical records from Lake TFL.

The overall pattern of dust flux in Lake TFL resembles that of global ice volume and bottom water temperatures, implying a connection to ice sheets and the broader climate system (Lisiecki & Raymo, 2005). It has previously been suggested that Northern Hemisphere ice sheets could modulate the Siberian High (e.g., Kang et al., 2022), which in turn may impact the low-level winds associated with the EAWM that supply dust to Lake TFL. On shorter timescales, we also find that there are instances where variations in Lake TFL dust fluxes do not correspond to changes in global ice volume, such as between 18 and 21 ka BP. Interestingly, this is a period (right before the HS1 event) where proxy data suggests a stronger AMOC prevailed (McManus et al., 2004). It has been suggested that the AMOC exerts an important role in driving the abrupt monsoon changes in East Asia via its effects on Northern Hemisphere meridional temperature gradients (Safaierad et al., 2020; Sun et al., 2012). Considering the similarities and differences between our dust flux record from Lake TFL, other dust records from the North Pacific Ocean and Greenland, global ice volume, and North Atlantic Ocean circulation, we suggest that high latitude cooling delivered cold air masses to northeastern China (Zheng et al., 2017) and enhanced the northwesterly winds linked to the EAWM (and likely also intensified the mid-latitude westerlies) over East Asia during the early LGM. Subsequently, the EAWM weakened across the deglaciation and remained weak during the Holocene, predominantly driven by Northern Hemisphere ice sheets and global temperatures. However, within the deglaciation, abrupt changes in AMOC may have provided an additional forcing mechanism on the EAWM, leading to periods of differences between our dust fluxes and the benthic oxygen isotope record (Figures 2l and 2m) (Lisiecki & Raymo, 2005; McManus et al., 2004).

In summary, new elemental and Nd-Sr isotopic compositions of sediments from a crater lake in northeastern China allow for the reconstruction of East Asian dust deposition over the past ~25 Kyr BP. Based on provenance analysis, we find that the EAWM is the dominant driver of dust input to Lake TFL across the LGM, deglaciation, and Holocene. By comparing our new dust flux record to other reconstructions of dust variations and the broader climate system, we propose that our data supports teleconnections between northeastern China, ice volume, and ocean circulation on sub-orbital time scales, and that shifts in these systems over the last ~25 Kyr BP led to rapid climate reorganizations in West Asia, Central Asia, as well as northeastern Asia (Kang et al., 2022; Safaierad et al., 2020; Sun et al., 2012).

Data Availability Statement

The major element and Nd-Sr isotope data used in this study are available online at the Figshare data repository link: https://figshare.com/articles/dataset/Dataset_of_Tuofengling_Lake_xlsx/22247866.

Acknowledgments
We thank Dr. Ming Ji, Dongliang Ning, Shouzhen Xin, and Qi Lin for assistance with field work. We thank Baichan Li, Weiwei Zhang, and Ye Li from NIGPAS for their assistance in the measurement of Nd and Sr isotopes. We thank the three anonymous reviewers for their constructive reviews of this paper. This work was financially supported by the National Natural Science Foundation of China (Grants 41888101 and 42025707). J.T.A. is currently supported by the U.S. NSF Division of Ocean Sciences Postdoctoral Fellowship (NSF-OCE-PRF #2126500).

References

Biscaye, P. E., Grousset, F. E., Revel, M., Van der Gaast, S., Zielinski, G. A., Vaars, A., & Kukla, G. (1997). Asian provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland. *Journal of Geophysical Research*, *102*(C12), 26765–26781. https://doi.org/10.1029/97JC01249

Blaauw, M., Christen, J. A., Bennett, K. D., & Reimer, P. J. (2018). Double the dates and go for Bayes—Impacts of model choice, dating density and quality on chronologies. *Quaternary Science Reviews*, *188*, 58–66. https://doi.org/10.1016/j.quascirev.2018.03.032

Bory, A. J. M., Biscaye, P. E., & Grousset, F. E. (2003). Two distinct seasonal Asian source regions for mineral dust deposited in Greenland (NorthGRIP). *Geophysical Research Letters*, *30*(4), 1167. https://doi.org/10.1029/2002GL016446

Chen, J., Li, G. J., Yang, J. D., Rao, W. B., Lu, H. Y., Balsam, W., et al. (2007). Nd and Sr isotopic characteristics of Chinese deserts: Implications for the provenances of Asian dust. *Geochimica et Cosmochimica Acta*, *71*(15), 3904–3914. https://doi.org/10.1016/j.gca.2007.04.033

Chiang, J. C. H., Fung, I. Y., Wu, C.-H., Cai, Y., Edman, J. P., Liu, Y., et al. (2015). Role of seasonal transitions and westerly jets in East Asian paleoclimate. *Quaternary Science Reviews*, *108*, 111–129. https://doi.org/10.1016/j.quascirev.2014.11.009

Fialkiewicz-Koziel, B., Bao, K., & Smieja-Krol, B. (2022). Geographical drivers of geochemical and mineralogical evolution of Motianling peatland (Northeast China) exposed to different sources of rare Earth elements and Pb, Nd, and Sr isotopes. *Science of The Total Environment*, *807*(Pt 1), 150481. https://doi.org/10.1016/j.scitotenv.2021.150481

Girty, G. H., Ridge, D. L., Knaack, C., Johnson, D., & Al-Riyami, R. K. (1996). Provenance and depositional setting of Paleozoic chert and argillite, Sierra Nevada, California. *Journal of Sedimentary Research*, *66*(1), 107–118. https://doi.org/10.1306/D42682CA-2B26-11D7-8648000102C1865D

Grousset, F. E., & Biscaye, P. E. (2005). Tracing dust sources and transport patterns using Sr, Nd and Pb isotopes. *Chemical Geology*, *222*(3–4), 149–167. https://doi.org/10.1016/j.chemgeo.2005.05.006

Hao, Q., Guo, Z., Qiao, Y., Xu, B., & Oldfield, F. (2010). Geochemical evidence for the provenance of middle Pleistocene loess deposits in southern China. *Quaternary Science Reviews*, *29*(23–24), 3317–3326. https://doi.org/10.1016/j.quascirev.2010.08.004

Ho, K.-S., Ge, W.-C., Chen, J.-C., You, C.-F., Yang, H.-J., & Zhang, Y.-L. (2013). Late Cenozoic magmatic transitions in the central Great Xing'an Range, Northeast China: Geochemical and isotopic constraints on petrogenesis. *Chemical Geology*, *352*, 1–18. https://doi.org/10.1016/j.chemgeo.2013.05.040

Jacobsen, S. B., & Wasserburg, G. J. (1980). Sm-Nd isotopic evolution of chondrites. *Earth and Planetary Science Letters*, *50*(1), 139–155. https://doi.org/10.1016/0012-821X(80)90125-9

Kang, S., Wang, X., Wang, N., Song, Y., Liu, W., Wang, D., & Peng, J. (2022). Siberian high modulated suborbital-scale dust accumulation changes over the past 30 ka in the eastern Yili Basin, Central Asia. *Paleoceanography and Paleoclimatology*, *37*(5), e2021PA004360. https://doi.org/10.1029/2021PA004360

Kang, S. G., Roberts, H. M., Wang, X. L., An, Z. S., & Wang, M. (2015). Mass accumulation rate changes in Chinese loess during MIS 2, and asynchrony with records from Greenland ice cores and North Pacific Ocean sediments during the Last Glacial Maximum. *Aeolian Research*, *19*, 251–258. https://doi.org/10.1016/j.aeolia.2015.05.005

Li, G., Chen, J., Ji, J., Yang, J., & Conway, T. M. (2009). Natural and anthropogenic sources of East Asian dust. *Geology*, *37*(8), 727–730. https://doi.org/10.1130/G30031A.1

Li, Y., Song, Y., Lai, Z., Han, L., & An, Z. (2016). Rapid and cyclic dust accumulation during MIS 2 in Central Asia inferred from loess OSL dating and grain-size analysis. *Scientific Reports*, *6*(1), 32365. https://doi.org/10.1038/srep32365

Liang, P., Chen, B., Yang, X., Liu, Q., Li, A., Mackenzie, L., & Zhang, D. (2022). Revealing the dust transport processes of the 2021 mega dust storm event in northern China. *Science Bulletin*, *67*(1), 21–24. https://doi.org/10.1016/j.scib.2021.08.014

Lin, X., Chang, H., Wang, K., Zhang, G., & Meng, G. (2020). Machine learning for source identification of dust on the Chinese Loess Plateau. *Geophysical Research Letters*, *47*(21), e2020GL088950. https://doi.org/10.1029/2020GL088950

Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography*, *20*(1), PA1003. https://doi.org/10.1029/2004PA001071

Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S., Yang, Q., Lyons, W. B., & Prentice, M. (1997). Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research*, *102*(C12), 26345–26366. https://doi.org/10.1029/96JC03365

McManus, J. F., Francois, R., Gherardi, J. M., Keigwin, L. D., & Brown-Leger, S. (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, *428*(6985), 834–837. https://doi.org/10.1038/nature02494

Peng, S., Hao, Q., Wang, L., Ding, M., Zhang, W., Wang, Y., & Guo, Z. (2016). Geochemical and grain-size evidence for the provenance of loess deposits in the Central Shandong Mountains region, northern China. *Quaternary Research*, *85*(2), 290–298. https://doi.org/10.1016/j.yqres.2016.01.005

Pratte, S., Bao, K., Sapkota, A., Zhang, W., Shen, J., Le Roux, G., & De Vleeschouwer, F. (2019). 14 kyr of atmospheric mineral dust deposition in north-eastern China: A record of palaeoclimatic and palaeoenvironmental changes in the Chinese dust source regions. *The Holocene*, *30*(4), 492–506. https://doi.org/10.1177/0959683619892661

R Development Core Team. (2010). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from http://www.R-project.org

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., et al. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, *55*(4), 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Rudnick, R. L., & Gao, S. (2014). Composition of the continental crust. In *Treatise on geochemistry* (2nd ed., pp. 1–51). https://doi.org/10.1016/B978-0-08-095975-7.00301-6

Ruth, U., Bigler, M., Röthlisberger, R., Siggaard-Andersen, M.-L., Kipfstuhl, S., Goto-Azuma, K., et al. (2007). Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate. *Geophysical Research Letters*, *34*(3), L03706. https://doi.org/10.1029/2006GL027876

Safaierad, R., Mohtadi, M., Zolitschka, B., Yokoyama, Y., Vogt, C., & Schefuss, E. (2020). Elevated dust depositions in West Asia linked to ocean-atmosphere shifts during North Atlantic cold events. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(31), 18272–18277. https://doi.org/10.1073/pnas.2004071117

Serno, S., Winckler, G., Anderson, R. F., Maier, E., Ren, H. J., Gersonde, R., & Haug, G. H. (2015). Comparing dust flux records from the Subarctic North Pacific and Greenland: Implications for atmospheric transport to Greenland and for the application of dust as a chronostratigraphic tool. *Paleoceanography*, *30*(6), 583–600. https://doi.org/10.1002/2014PA002748

Sun, Y. B., Clemens, S. C., Morrill, C., Lin, X. P., Wang, X. L., & An, Z. S. (2012). Influence of Atlantic meridional overturning circulation on the East Asian winter monsoon. *Nature Geoscience*, *5*(1), 46–49. https://doi.org/10.1038/ngeo1326

Tsai, F., Chen, G. T. J., Liu, T. H., Lin, W. D., & Tu, J. Y. (2008). Characterizing the transport pathways of Asian dust. *Journal of Geophysical Research*, *113*(D17), D17311. https://doi.org/10.1029/2007JD009674

Vandenberghe, J., Renssen, H., van Huissteden, K., Nugteren, G., Konert, M., Lu, H., et al. (2006). Penetration of Atlantic westerly winds into Central and East Asia. *Quaternary Science Reviews*, *25*(17–18), 2380–2389. https://doi.org/10.1016/j.quascirev.2006.02.017

Xie, Y., Yuan, F., Zhan, T., Kang, C., & Chi, Y. (2018). Geochemical and isotopic characteristics of sediments for the Hulun Buir Sandy Land, northeast China: Implication for weathering, recycling and dust provenance. *Catena*, *160*, 170–184. https://doi.org/10.1016/j.catena.2017.09.008

Yang, S., & Ding, Z. (2008). Advance-retreat history of the East-Asian summer monsoon rainfall belt over northern China during the last two glacial-interglacial cycles. *Earth and Planetary Science Letters*, *274*(3–4), 499–510. https://doi.org/10.1016/j.epsl.2008.08.001

Zaarur, S., Stein, M., Adam, O., Mingram, J., Liu, J., Wu, J., et al. (2020). Synoptic stability and anomalies in NE China inferred from dust provenance of Sihailongwan maar sediments during the past ~80 kyr. *Quaternary Science Reviews*, *239*, 106279. https://doi.org/10.1016/j.quascirev.2020.106279

Zhao, W. (2015). *Geochemistry characteristics of clay-sized fractions from East Asian deserts-Mineral dust provenance, transport and tracer*. (Doctoral dissertation). Nanjing University.

Zhao, W., Sun, Y., Balsam, W., Zeng, L., Lu, H., Otgonbayar, K., & Ji, J. (2015). Clay-sized Hf-Nd-Sr isotopic composition of Mongolian dust as a fingerprint for regional to hemispherical transport. *Geophysical Research Letters*, *42*(13), 5661–5669. https://doi.org/10.1002/2015GL064357

Zhao, Y., & Fan, Q. (2012). Mantle sources and magma genesis of Quaternary volcanic rocks in the Halaha River and Chaoer River area, Great Xing'an Range. *Acta Petrologica Sinica*, *28*(4), 1119–1129. (in Chinese with English Abstract). Retrieved from http://www.ysxb.ac.cn//article/id/aps_20120409

Zheng, Y., Pancost, R. D., Liu, X., Wang, Z., Naafs, B. D. A., Xie, X., et al. (2017). Atmospheric connections with the North Atlantic enhanced the deglacial warming in northeast China. *Geology*, *45*(11), 1031–1034. https://doi.org/10.1130/G39401.1

Zhou, X., Zhan, T., Tan, N., Tu, L., Smol, J. P., Jiang, S., et al. (2023). Inconsistent patterns of Holocene rainfall changes at the East Asian monsoon margin compared to the core monsoon region. *Quaternary Science Reviews*, *301*, 107952. https://doi.org/10.1016/j.quascirev.2022.107952

Zhu, J., Mingram, J., & Brauer, A. (2013). Early Holocene aeolian dust accumulation in northeast China recorded in varved sediments from Lake Sihailongwan. *Quaternary International*, *290–291*, 299–312. https://doi.org/10.1016/j.quaint.2012.10.057

References From the Supporting Information

Jweda, J., Bolge, L., Class, C., & Goldstein, S. L. (2016). High precision Sr-Nd-Hf-Pb isotopic compositions of USGS reference material BCR-2. *Geostandards and Geoanalytical Research*, *40*(1), 101–115. https://doi.org/10.1111/j.1751-908X.2015.00342.x

Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., et al. (2000). JNdi-1: A neodymium isotopic reference in consistency with LaJolla neodymium. *Chemical Geology*, *168*(3), 279–281. https://doi.org/10.1016/S0009-2541(00)00198-4

Ujvari, G., Klotzli, U., Horschinegg, M., Wegner, W., Hippler, D., Kiss, G. I., & Palcsu, L. (2021). Rapid decomposition of geological samples by ammonium bifluoride (NH_4 HF_2) for combined Hf-Nd-Sr isotope analyses. *Rapid Communications in Mass Spectrometry*, *35*(11), e9081. https://doi.org/10.1002/rcm.9081

Zhang, W., Zhao, J.-x., Chen, J., Ji, J., & Liu, L. (2018). Binary sources of Chinese loess as revealed by trace and REE element ratios. *Journal of Asian Earth Sciences*, *166*, 80–88. https://doi.org/10.1016/j.jseaes.2018.07.017