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Dust variation recorded by lacustrine sediments from arid Central Asia since ~15 cal ka BP and its implication for atmospheric circulation

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ABSTRACT

A long dust history established using geological archives from dust provenance areas is necessary to understand the role of atmospheric dust in the global climate system better. Core sediments from a closed-basin groundwater-recharged lake in arid Central Asia were investigated using a multi-proxy approach (e.g. ^{14}C AMS dating, pollen, and grain size) to trace the dust history since ~15 cal ka BP. Pollen analysis showed that before 7.9 cal ka BP, the vegetation was of desert type. After 7.9 cal ka BP, vegetation density increased, probably due to slightly increased moisture. The Chenopodiaceae-dominated desert expanded rapidly at 4.2–3.8 cal ka BP. Grain-size analysis was conducted for samples of lake deposits, modern aeolian dust, and dust trapped in snow, and the data showed that there was strong aeolian dust deposition at 11.8–11.1, 10.6–8, 6.1–4.9, and after 3.3 cal ka BP. This timing corresponds well with periods of increased terrestrial dust fluxes recorded by Greenland ice cores. Our study may document changes in the location and intensity of the Siberia High. These changes may play a more important role in the history of dust emission in arid Central Asia than previously thought.

Introduction

Wind-borne (aeolian) dust strongly affects agricultural productivity and various aspects of human, plant and animal life. Both directly and indirectly, aeolian dust influences the atmospheric radiation balance, and hence global climatic variations, as the largest source of aerosols. Thus, investigation of dust history will expand our understanding of ocean–atmosphere–land interactions in the climate system.

Dust storms from major Asian sources are usually carried by westerly winds over northern China to the Pacific Ocean (Pye and Zhou, 1988; Rea and Leinen, 1988). Ice cores drilled at Summit, Greenland contain a record of environment change through glacial–interglacial cycles (Johnsen et al., 1992). The clay mineralogy and isotope composition of dust in the ice and in possible source areas from around the northern hemisphere, Biscaye et al. (1997) concluded that the most likely sources are in Asia, specifically the Chinese Loess Plateau and the Gobi Desert, and possibly other northwestern desert lands. Most of this area is in so-called arid Central Asia, a region extending from the Caspian Sea in the west to the modern Asian summer monsoon limit in the east (Fig. 1), that is one of the largest arid (desert) areas and dust sources in the world (Dando, 2005; Chen et al., 2010). Dust generated during a storm in arid Central Asia was transported more than one full circuit around the globe in about 13 days (Uno et al., 2009).

Long-range transport of desert dust during late winter and spring in arid Central Asia is well-documented (e.g. Shaw, 1980; Prospero and Savoie, 1989; Murayama et al., 2001; Hara et al., 2006). Many researchers have noted the effect of the high aerosol load caused by frequent Asian dust outbreaks on visibility, biogeochemical cycles, and the atmospheric radiation budget (e.g. Uematsu et al., 1983; Li et al., 1996; Chun et al., 2001; Seinfeld et al., 2004). Changes in wind strengths have been invoked to account for the changes in dust and grain size documented by lacustrine sediments in arid Asia (Qiang et al. 2007; Sorrel et al., 2007).

That ice-core data reveal glacial periods to be far dustier than interglacial periods, is well known (e.g. Petit et al., 1981; Mayewski et al., 1994; Thompson et al., 1995). However, there has been little effort to evaluate temporal change in dust production from the provenance areas directly. Though historic (Zhang, 1984), lacustrine (Qiang et al. 2007; Sorrel et al., 2007) and multi-archive (Yang et al. 2007) records of dust history exist for the last millennium, spatial and temporal records of dust-storm frequency in arid Central Asia are limited. New work will strengthen our understanding of the history of aeolian dust and its relationship with environmental change across this poorly documented region. Hydrologically closed lakes in arid Central Asia are natural dust traps that provide an excellent opportunity to examine paleoenvironmental change, particularly long-term change associated with aeolian dust deposition.

Here we present a Late-Glacial and Holocene dust-frequency record inferred by grain-size analysis of sediments extracted from

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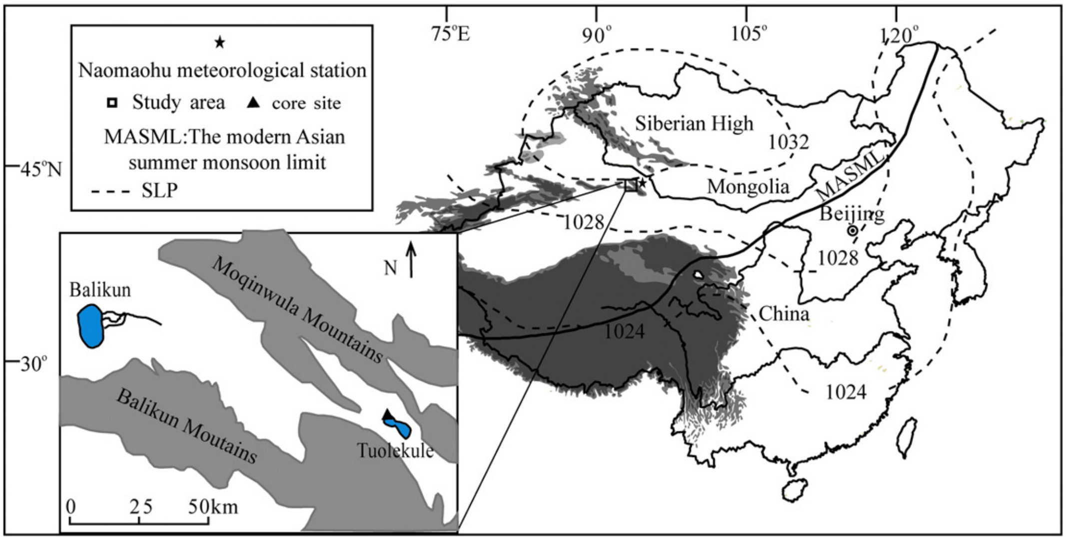

Figure 1. Location map of the study area. Winter (Dec.–Feb.) mean sea level pressure (SLP, hPa) for 1958–1999 (Wu and Wang, 2002). The modern Asian summer monsoon limit (Gao, 1962; Chen et al., 2010).

Lake Tuolekule, which is located in eastern Xinjiang, China (Fig. 1). Our record provides new information concerning the environmental and climatic history of arid Central Asia since ~15 cal ka BP, with special emphasis on aeolian dust expressed by grain size in connection with the main pattern of spring Siberian high-pressure system. The cores from Lake Tuolekule offer an excellent opportunity to compare Late-Glacial and Holocene dust records from the source area with dust records archived in Greenland ice. The record from Lake Tuolekule will allow us to determine whether dust fluctuations found in sediment cores from Lake Tuolekule result from fluctuations in local climate, or are the result of more extensive, regional patterns. Therefore, this study sheds light on changes in aeolian dust dynamics in connection with the main pattern of the Siberian high pressure system since ~15 cal ka BP in arid Central Asia, expands our knowledge of dust history in the provenance areas, and will enhance our understanding of dust transport and thereby global atmospheric circulation.

Materials and methods

Site and coring

Lake Tuolekule (43°18′–43°23′N, 94°09′–94°16′ E) fills a Mesozoic depression at 1890 m above sea level on the eastern part of Xinjiang Province, China about 500 km far from the core area of the Siberian High (Wu and Wang, 2002) and about 95 km from Balikun Lake (Fig. 1). This 2.8 km wide lake extends 10.3 km along a northwest to southeast axis, with a surface area of ~29 km^2 and a watershed catchment of 1000 km^2. No major rivers drain into Tuolekule which is instead recharged by groundwater and by small ephemeral rivers originated from springs. This results in a salinity of 269.9 g/l. The lake bed is flat and the water depth is 0.2–0.4 m (Wang and Dou, 1998). The local climate is characterized by a strong seasonal contrast between warm summers and cold winters with prevailing westerly winds. The mean annual precipitation is 98 mm, and average annual temperature is 3.5°C (Guo, 2010). Modern vegetation in the area is of the Gobi Desert community (Editorial board, 1990).

In March 2006, two 446-cm-long parallel sediment cores were extracted from the northwest dry lake bed using piston coring equipment. The near-shore location of the cores in the semi-closed bay, a stable sedimentation environment without river or spring inflow, allowed us to obtain a continuous aeolian dust record. This study focuses on the upper 270 cm of the core (Fig. 2). Sediment subsamples of the cores were taken every 1 cm for grain-size analysis and every 6 cm for pollen analysis. Accelerator mass spectrometry (AMS) radiocarbon ages from six levels in the cores were determined from bulk organic matter at the AMS Dating Laboratory of Beijing University and a complementary lacustrine sample collected in 2010 was measured in Beta Analytic, Inc. Calibrated ages were determined by CALIB 5.0 program with the INTCAL04 model (Reimer et al., 2004). Results are reported in Table 1.

Grain size and pollen analysis

Grain size was measured using a Malvern Co. Ltd. Mastersizer 2000 laser diffraction particle-size analyzer. Before the grain-size analysis, samples were treated with 10–20 ml of 30% H_2O_2 to remove organic matter, washed with 10% HCl to remove carbonate, rinsed with deionized water, and then treated with 10 ml of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min to facilitate dispersion. Aeolian dust samples trapped in the study area were collected as reference material.

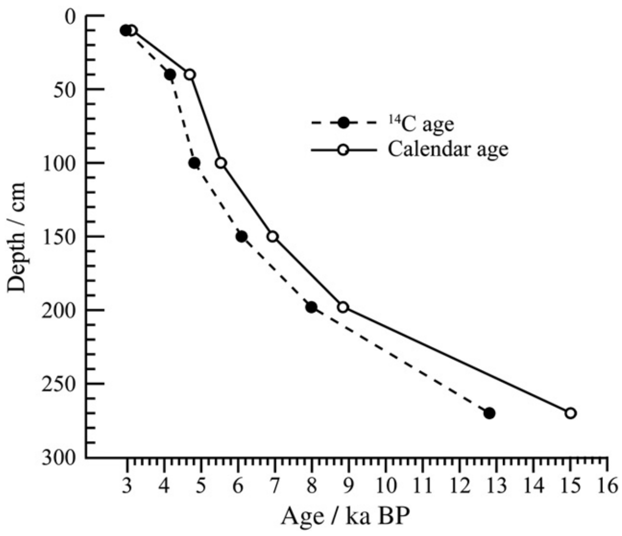

Figure 2. Radiocarbon ages versus depth in the cores of Lake Tuolekule. For details see text.

Table 1
AMS ^{14}C dates from the Lake Tuolekule core sediments.

Lab no.	Sample no.	Depth (cm)	Dating material	^{14}C age (^{14}C yr BP)	δ^{13}C (‰)	Calendar age (2σ) (cal yr BP)
LAMS06-094[a]	TLKL-G10	10	Bulk sediment	2955 ± 40	−36.27	2988–3257
LAMS06-095[a]	TLKL-G40	40	Bulk sediment	4155 ± 40	−23.95	4569–4830
LAMS06-096[a]	TLKL-G100	100	Bulk sediment	4815 ± 40	−31.47	5468–5613
LAMS06-097[a]	TLKL-G150	150	Bulk sediment	6095 ± 40	−13.67	6856–7031
LAMS06-098[a]	TLKL-G198	198	Bulk sediment	7985 ± 50	−41.19	8695–9006
LAMS06-099[a]	TLKL-G270	270	Bulk sediment	12810 ± 60	−44.47	14900–15143
288770[b]	TLKL10-54	54	Bulk sediment	1770 ± 40	−24.4	1810–1570

[a] AMS ^{14}C Laboratory of Beijing University.
[b] Beta Analytic Inc.

The subsamples for pollen analysis were processed with the standard method including HCl, NaOH, HF, and Acetolysis treatments. Before the chemical procedure, tablets containing a known quantity of *Lycopodium* spores (batch # 938934) were added as exotic markers into the samples to determine pollen concentration. Approximately 5 g of sample was digested with 10% HCl, 10% KOH, 40% HF, then filtered with a 7 μm mesh sieve. Each pollen sample was counted under a light microscope at 400× magnification in regularly spaced traverses. For most samples, more than 300 terrestrial plant pollen grains (Fig. 5) were counted. All pollen and spores were identified to genus or family level. Identifications of pollen followed Wang et al. (1995) and Xi and Ning (1994) aided by a modern reference collection. Pollen percentages were calculated based on the total terrestrial pollen sum.

Results

Chronology

The ^{14}C age–depth correlation is shown in Figure 2. Six AMS ^{14}C dates were obtained on bulk sediment samples by the AMS ^{14}C Laboratory of Beijing University (Table 1). Calibration of the AMS ^{14}C dates was done using the CALIB 5.0 program (Reimer et al., 2004). An age model was then constructed by linear interpolation between absolute dates (Fig. 2).

In arid and semi-arid areas, the reservoir effect may complicate radiocarbon dating. For this study, the interpolated age model suggests the AMS ^{14}C age at the top of the core is about 2555 ^{14}C yr BP. It is suggested that this is caused by erosion rather than reservoir effect. Because intense human activity in the region over the past few decades has reduced the total size of Lake Tuolekule (Hu et al., 1994), core sampling was conducted on dry land that was underwater in recently. Therefore, the upper-most portion of the core (spanning ca. 2–3 ka) may have eroded recently.

On the other hand, the carbonate content of Lake Tuolekule is less than 10% in most samples (unpublished data) and, at the same time, the organic matter content is less than 5% (unpublished data). Thus it appears that productivity of the lake was very low, and that organic matter in the core samples comes primarily from terrestrial plant pollen transported by wind. This is supported by the light δ^{13}C value of the AMS dating samples. Many studies show that terrestrial organic matter has relatively light δ^{13}C values, whereas aquatic organic matter in Xinjiang characteristically has heavy δ^{13}C (Wang, 2001; Xu et al., 2002; Zhang et al., 2003a,b; Ma et al., 2006, 2007). Accordingly, old carbon and aquatic plants have little or no effect on the AMS ^{14}C age of the bulk sediment of Lake Tuolekule. At the thoroughly studied Lake Balikun the contents of carbonate and organic matter are higher than Tuolekule Lake, and the reservoir-effect correction there is only ca. 790 yr (Tao et al., 2010).

Thus, while our chronology may be off by a little due to the uncorrected reservoir effect, it is likely a small error that does not affect the main aims of this paper. In order to test this hypothesis, we dated a lacustrine sample that is still underwater nowadays. Considering the disturbance caused by intensive human activity during recent decades, this sample was not collected at the top part of lake sediments, but at the depth of 54 cm. The ^{14}C age of this sample is 1770 ± 40 ^{14}C yr BP (Table 1). Meanwhile, if we take the age of the top modern lacustrine sediment as −60 ^{14}C yr BP (2010 AD), the age of the lacustrine sample at depth 54 cm extrapolated by the core sedimentation rate is 1560 ^{14}C yr BP. This result implies that the reservoir effect in this lake is ~200 ^{14}C yr BP and that our chronology is reliable.

Furthermore, in order to verify the reliability of the dates we compare the age framework of Balikun Lake with the age of this lake. The distance between lakes Balikun and Tuolekule is ~95 km (Fig. 1). The age framework of Balikun is cross-validated and reliable (Tao et al., 2010).

For the purpose of this study we performed the following steps to finish the comparison: ① calibration of radiocarbon dates from Tuolekule (Table 1); ② application of the established age–depth model to the pollen records of Tuolekule; and ③ comparison of the pollen record of this study with the result of Balikun. To our satisfaction, both pollen records demonstrate a parallel trend. For instance, the pollen record of Balikun show that vegetation density increased from 7.9 cal ka BP and the climate became wet from that time on. A brief but extremely arid climatic event occurred during 4.3–3.8 cal ka BP (Tao et al., 2010). The pollen record of this study shows that a suddenly increasing of vegetation dense occurred 7.9 cal ka BP and the vegetation quickly changed from steppe-desert to desert at around 4 cal ka BP. This comparison strengthens the chronology of Tuolekule.

In fact, a recent study shows that the reservoir effect in lacustrine sediments in arid China can be negligible (Long et al., 2011).We suspect that multi-method dating in a future study will corroborate our ^{14}C chronology.

Grain size

Size analysis of aeolian dust grains from lacustrine sediments is widely used as a climate proxy (Deckker et al., 1991; Xiao et al., 1997; Jin et al., 2000; Sun and Xiao, 2006). Grain-size analyses for the sediments in the cores from Lake Tuolekule reveal a uniform grain-size distribution (Fig. 3A). They all possess the same modal grain size of ~10 μm (silt). Occasionally there is a very small peak at 100–1000 μm (sand).

Aeolian dust samples trapped in the area during January–March, and April–Jun, 2009, show almost the same grain-size distribution, with a similar modal grain size of ~10 μm (Fig. 3B), and a small peak at 100–1000 μm, suggesting sediments in the lake are most likely related to aeolian dust. Thus the grain-size variation of the lake sediments can be used to describe changes in the sedimentary environment related to aeolian dust. Samples of dust trapped in snow before melting season demonstrate a similar grain size distribution (Fig. 3B). Because the lake is not fed by major rivers, sediments appear to have been transported mainly by wind. Dust samples collected in northern China in the years 1994 and 1998 have median grain sizes comparable to the grain size data for sediments from Lake Tuolekule (Liu et al., 2004), enhancing this explanation.

The mean grain size and the fraction >63 μm show the clearest signal (Fig. 4). The mean grain size varies from 8 to 45 μm, while the

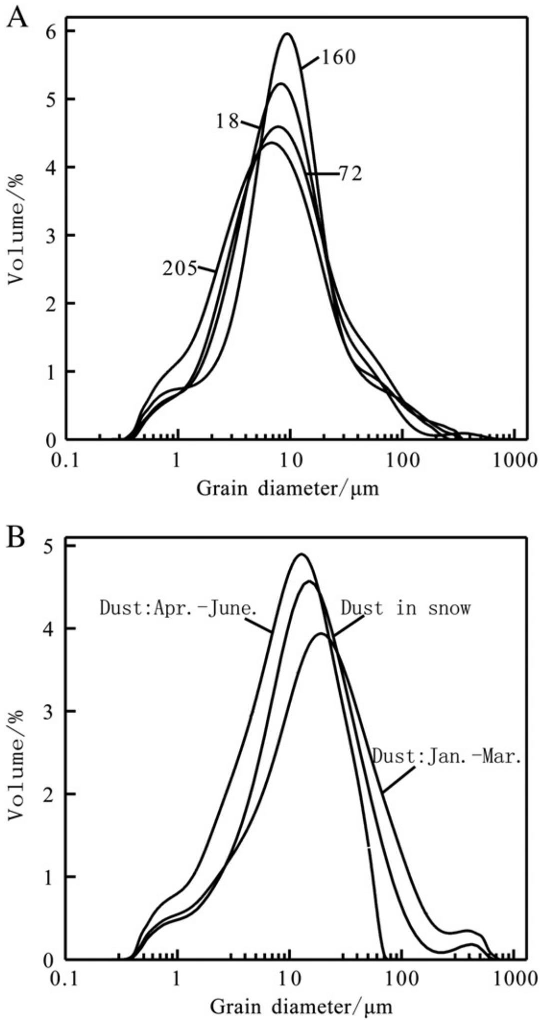

Figure 3. Grain size distribution of samples of the cores sediment of the Lake Tuolekule (A) and aeolian dust samples (B) collected in the study area. The aeolian dust sample trapped in snow was collected in spring before melting. The numbers in (A) panel represent the depth of samples.

coarser mean grain size (>25 μm) appeared at 11.8–11.1 cal ka BP, 10.6–8 cal ka BP, 6.1–4.9 cal ka BP, and 3.3–2.4 cal ka BP, and relatively fine grain size (>15 μm) appeared at 14.3–13 cal ka BP and 7.4–6.5 cal ka BP. The percentage of the >63 μm fraction varies between 1% and 14%. A high percentage of this coarse fraction occurred during 11.8–11.1 cal ka BP, 10.6–8 cal ka BP, 6.1–4.9 cal ka BP, and 3.3–2.4 cal ka BP. There are also two smaller peaks at 14.3–13 cal ka BP and 7.4–6.5 cal ka BP.

The four stages of coarser mean grain size found in this study correspond well with the periods of high concentrations of terrestrial dust found in Greenland ice cores (O'Brien et al., 1995; Mayewski et al., 1997). Concentrations of terrestrial dusts increased in Greenland ice records during the periods more than 11.3 cal ka BP, 8.8–7.8 cal ka BP, cal ka BP, 6.1–5 cal ka BP, and 3.1–2.4 cal ka BP.

Pollen

All fossil pollen spectra (Fig. 5) show high frequencies of *Artemisia*, Gramineae, Compositae, Chenopodiaceae, and *Ephedra* which sum up to more than 80% in most samples. Tree pollen occur with very low frequencies (<5%).

Chenopodiaceae and *Ephedra* are assumed to indicate desert conditions, whereas *Artemisia* indicates steppe conditions. *Artemisia*, Gramineae, Compositae, Chenopodiaceae, and *Ephedra* are often the dominant taxa in arid regions lacking forest vegetation. The percentage pollen diagram can be divided into two pollen assemblage zones as shown below.

Zone 1 (15–7.9 cal ka BP) is dominated by Compositae (25–47%) and *Ephedra* (30–46%), other Gramineae, and Chenopodiaceae. Zone 2 (7.9–2.4 cal ka BP) has more kinds of pollen. The pollen assemblages are characterized by high value of *Artemisia* (8–30%), Gramineae (10–40%), and Chenopodiaceae (25–80%). At 4.2–3.8 cal ka BP, Chenopodiaceae reaches its maximum value (~80%).

This sequence of pollen indicates that vegetation changed from *Ephedra*–Compositae dominated desert before 7.9 cal ka BP, to steppe-desert, consisting mainly of *Artemisia*, Gramineae, and Chenopodiaceae after 7.9 cal ka BP, and later, a rapid expansion of Chenopodiaceae-dominated desert at 4.2–3.8 cal ka BP. The vegetation suggests a consistently dry climate at 15–7.9 cal ka BP. Though pollen density and richness suggest that vegetation density increased somewhat after 7.9 cal ka BP, the region remained generally dry.

Discussion

Dust and the Siberian High

As presented above, the sediments of cores from Lake Tuolekule are primarily aeolian dust. Lake Tuolekule lies in a basin characterized

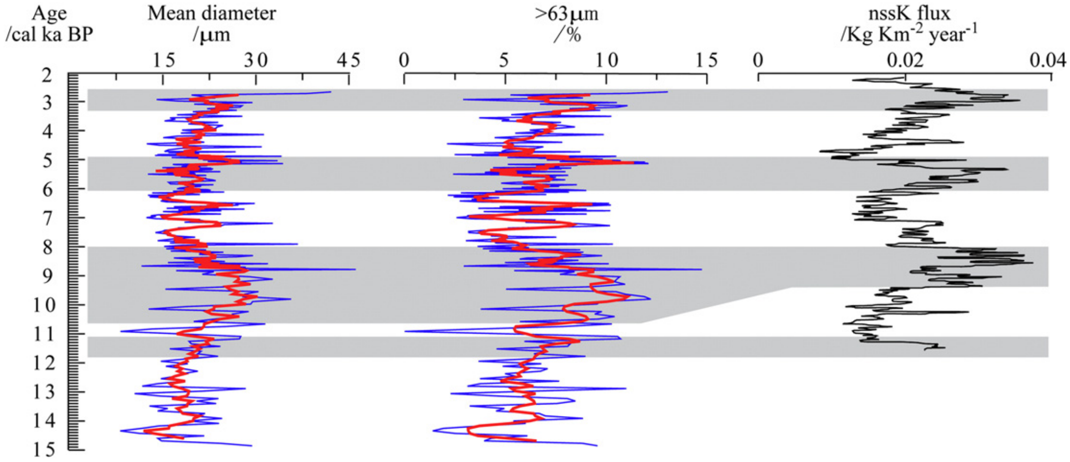

Figure 4. Grain size of cores recovered from Lake Tuolekule and its correspondence with concentration of terrestrial dust during the Holocene as reported in the Greenland ice core (O'Brien, et al., 1995; Mayewski et al., 1997). The red lines represent a 5-point running average. The gray shaded areas show the correspondence.

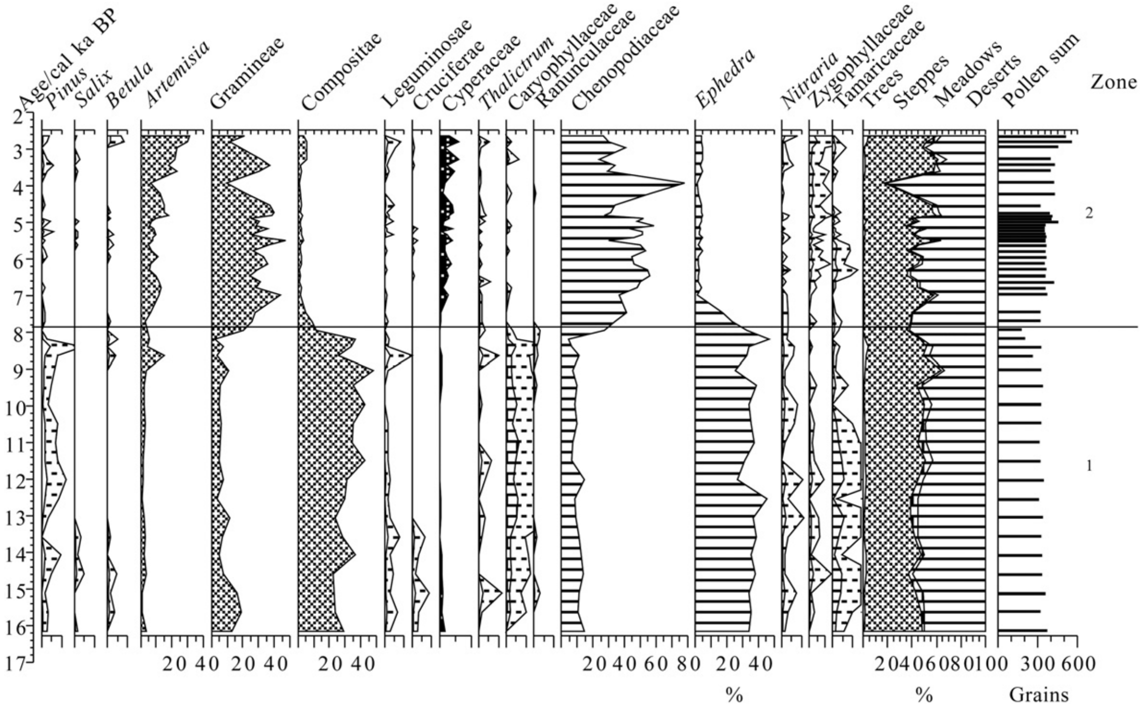

Figure 5. Percentage pollen diagram of Lake Tuolekule.

by Gobi Desert vegetation, and dust transported by the dominant western and northwestern winds (Ayixiamu, 2004) likely controls the sediment accumulation in the cores. In the study area, most dust events occur during the spring (68%) and summer (14.4%), mainly due to the increased intensity of the general circulation associated with seasonal warming and more energetic synoptic cyclone activity (Zhou and Zhang, 2003; Daoran-Japayi and Ayixiamu, 2004). Therefore, because the dust results from atmospheric circulation on a broad scale are associated with seasonal temperature and pressure gradients, it is important to examine the connections between dust production, transport, and deposition, and climate dynamics.

The Siberian High anticyclone is broadly recognized as the dominant mode of winter and spring climate over Eurasia (Sahsamanoglou et al., 1991; Savelieva et al., 1991; Panagiotopoulos et al., 2005). Observations from the Naomaohu meteorologic station (location shown in Fig. 1), ~70 km to the northeast of Lake Tuolekule, show that between 1961 and 2000 AD, aeolian sand and dust transport occurred most commonly in the spring, then in summer and least in winter. It was a high-frequency period for sandy and dusty weather from the 1960s to the 1970s, which was much decreased from 1983 to 2000 (Daoran-Japayi and Ayixiamu, 2004).

This corresponds well with the variation of Siberia High (Fig. 6). The Siberian high played a more significant role in dusty weather before the 1980s. In the 1960s, the Siberian High was characteristically intense corresponding to frequent dusty weather. Though the intensity of the Siberian High decreased somewhat during the 1970s, positive anomalies still corresponded with dusty weather. During the 1980s and 1990s, the intensity of the Siberian High was low and this corresponded with infrequent dusty weather (Gong and Wang, 1999). This trend of Asian dust is consistent with that found in previous studies not only in the Gobi and desert source region (Sun et al., 2001; Zhang et al., 2003a,b) but also in other parts of China and Japan (Zhou et al., 2002; Zhou and Zhang, 2003; Hara et al., 2006). Apparently, the frequency of sandy or dusty weather is closely related to the intensity of the Siberian High in this study area: the stronger the Siberian High, the greater the frequency of dust storms.

This relationship between dust-storm frequency and the intensity of the Siberian High is not only documented by instrumental data, but also by proxy records. Together, glaciochemical series from the GISP2 Ice Core are always associated with a spring strengthening of the Siberian High pressure system located at the provenance area of the dust (Mayewski et al., 1997; Meeker and Mayewski, 2002). This finding is supported by a high-resolution lacustrine record from the Aral Sea (Sorrel et al., 2007) in western Central Asia. Their results demonstrate that during the last 1500 yr, high detrital inputs were associated with an increase in the intensity of the Siberian High pressure system.

The link between Greenland ice and the Asian landmass has also been reported at millennial-scale (Porter and An, 1995; Ruth et al., 2007). A review of records of aeolian deposition from the Chinese

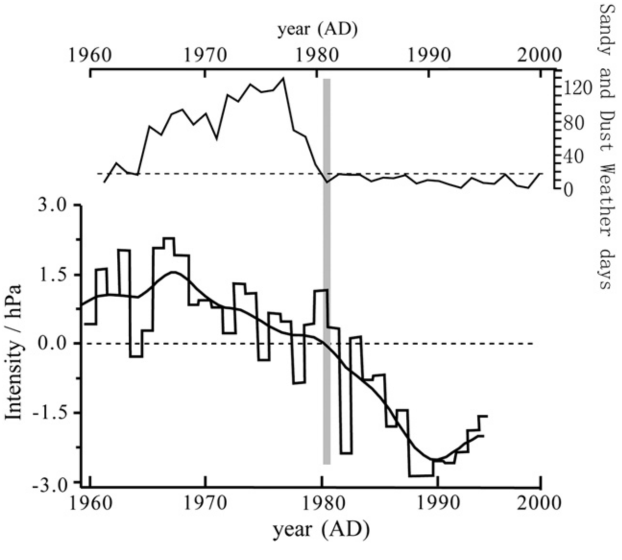

Figure 6. Comparison between sandy and dust weather days in Naomaohu meteorological station (upper panel) (Daoran-Japayi and Ayixiamu, 2004) and anomalies of winter Siberian High intensity (lower panel) (Gong and Wang, 1999). The anomalies of winter Siberian High intensity are relative to 1961–1990 and smoothed with a 9-point Gaussian filter. The gray shaded areas represent the knee point of dusty weather days and anomalies of winter Siberian High intensity.

Loess Plateau shows that that there are significant millennial-scale variations in dust accumulation (Kohfeld and Harrison, 2003). The records from the Chinese Loess Plateau show high dust accumulation during the late glacial and early Holocene periods, corresponding well with this study. The timing of the onset of reduced dust accumulation varies from site to site in the Chinese Loess Plateau during the mid-Holocene, and may reflect spatial patterning in the timing of increased monsoonal rainfall (Kohfeld and Harrison, 2003) rather than changes in the source area of the dust. The difference may be about proximity to different weather systems: Lake Tuolekule is about 500 km from the core of the Siberian High while the Chinese Loess Plateau is dominated by the East Asia Monsoon. In the study region, regional pressure distribution in combination with rising temperatures over the continent appeared to cause the evaporation of the weak seasonal precipitation and the drying of the upper silty and sandy surface beds, both favourable conditions for the formation of dust storms during spring (Ayixiamu, 2004; Daoran-Japayi and Ayixiamu, 2004).

Therefore, in Lake Tuolekule, time periods characterized by coarse grain sizes probably stem from a stronger Siberia High during enhanced spring meridional atmospheric circulation. The mean grain size and fraction >63 μm with peaks at 4 different times correspond well with increased terrestrial dust during the periods before 11.3, 8.8–7.8, 6–5, and 3.1–2.4 cal ka BP recorded in Greenland ice (O'Brien et al., 1995) (Fig. 4). Our study site, about 500 km from the core of the Siberian High, may document the intensity of the Siberian High in geological history.

Causes of dust

Many studies have been undertaken to clarify the relationship between Asian dust and climate indices. In the study area, it is the wind gusts that matter for dust generation, and that these wind gusts peak in the spring (Ayixiamu, 2004; Daoran-Japayi and Ayixiamu, 2004).

The springtime peak in Asian dust outbreaks is well-known from the modern record, and the meteorological causes have been studied in detail (e.g., Sahsamanoglou et al., 1991; Parungo et al., 1994; Uno et al., 1998; Husar et al., 2001; Zhou and Zhang, 2003; Kurosaki and Mikami, 2004; Qian et al., 2004; Aoki et al., 2005; Roe, 2009). The peak wind gusts are associated with the passage of strong, and largely dry, cold fronts. Major dust outbreaks in northern China over the last 50 yr have been associated with large-scale cold air surges from Siberia (Zhou and Zhang, 2003). Although details such as location and intensity differ from storm to storm, this basic picture of dust outbreaks generated by windstorms associated with the passage of cold fronts is repeated for all of the major dust storms (Zhou and Zhang, 2003).

In springtime cold air builds over Siberia during quiescent periods, and during synoptic development of mid-latitude storms, this cold air is drawn southward. Strong gusts at the leading front of this cold surge loft dust into the atmosphere where it is transported by the prevailing winds. During the passage of a cold front, the cold, dense air plunges through a gap in the mountains at the western end of the basin containing Lake Balikun and Lake Tuolekule. Thus, like the primarily westerly large-scale flow, the local, low-altitude winds that raise the dust in the basin are westerly at the time of the windstorm.

Increased intensity of atmospheric circulation during the breakdown of the Siberian High may be the most important factor controlling dust storms in the region. Roe (2009) concluded that it is the breakdown of the Siberian High that permits the occurrence of dust storms. He assumed that the Siberian High is weak in spring and fall and absent in summer, and so the atmosphere is less resistant to vertical displacement during those seasons than it is in winter. In spring, a reservoir of cold air still exists in the north, but the sun has begun to warm the land in the lower mid-latitudes. This leads to the large climatological temperature gradients capable of generating intense cold fronts. By summer, however, even the high latitudes have warmed, and the meridional temperature gradients are consequently weakened. Fall temperatures look quite a lot like those in the spring, although there are some subtle, but apparently important, differences. In fall, the location of the coldest air is displaced eastward compared to spring, and east of the major dust-generating regions. A case study based on meteorological data and modeling show that a decline in the frequency of dust days in the source areas results from a decreasing frequency of strong winds (Hara et al., 2006). Additionally, their results show that abundant dust emissions in the Gobi Desert region of central Asia are associated with cold-air invasion from higher latitudes. Wind speed, along with factors associated with long-range transport, is likely to be a dominant cause of dust entrainment. This argument is supported by studies based on instrument data in both the study area (Ayixiamu, 2004; Daoran-Japayi and Ayixiamu, 2004) and surrounding regions (Sun et al., 2001; Zhou et al., 2002; Zhang et al., 2003a,b; Fan and Wang, 2006; Zhang et al., 2010), and in glaciochemical series from the GRIP Ice Core (Fuhrer et al., 1999).

Increased aridity is also often suggested as a possible explanation for dust storms (e.g. Rea, 1994; Chen et al., 2003; Mischke et al., 2010). This is not supported by the dust history documented at Lake Tuolekule. For instance, the high frequency of dust at 10.6–8 cal ka BP corresponds to the dry period recorded by fossil pollen from Balikun (Tao et al., 2010) and this study. But there is no evidence of increasing aridity after 3.3 cal ka BP corresponding with the high frequency of dust in both lakes. By contrast, the increase in *Artemisia* pollen suggests increasing humidity during this period, and this is consistent with a rise in lake levels from 3 to 2 ka in western Mongolia (Grunert et al., 2000). We therefore propose that increased aridity may be one factor that influences the dust emission, though it is not the controlling factor.

In summary, several factors contribute to the frequency of sandy and dusty weather in eastern Eurasia. First, wind gusts are largely responsible for dust generation, which peaks in the spring (e.g. Zhou and Zhang, 2003; Kurosaki and Mikami, 2004; Roe, 2009). Second, the interaction between cold air masses and the local synoptic cyclone enhance wind strength and increase their frequency (Daoran-Japayi and Ayixiamu, 2004; Fan and Wang, 2006; Zhang et al., 2010). These two factors are both directly and indirectly related to the intensity and breakdown of the Siberian High. Other factors such as the Southern Oscillation (Hara et al., 2006), the Antarctic Oscillation (Fan and Wang, 2004), are also related to wind strength.

We propose that variations in grain size seen in sediment cores from Lake Tuolekule are mainly the result of change in the intensity of wind energy: the stronger the winds, the coarser the grains brought into the lake. Periods characterized by coarse grain size can be interpreted as having significantly increased aeolian dust and wind strength. A similar result was observed in studies of desert loess by (Crouvi et al., 2009, 2010).

Conclusion

The sediment cores from the Lake Tuolekule represent a Late-Glacial and Holocene record of dust deposition and provide additional information with respect to the vegetation evolution. Pollen analysis shows that before 7.9 cal ka BP, the vegetation was sparse desert, evolved under harsh environmental conditions. After 7.9 cal ka BP, a relatively dense vegetation was established, probably as a result of a slight increase of moisture, but conditions were still dry in general. There was a rapid expansion of Chenopodiaceae-dominated desert at 4.2–3.8 cal ka BP.

Grain-size analysis shows that time periods characterized by coarse grain size probably indicate stronger Siberian Highs during enhanced spring meridional atmospheric circulation. The mean grain size and fraction >63 μm peaking at 11.8–11.1, 10.6–8, 6.1–4.9, and after 3.3 cal ka BP correspond well with increased terrestrial dust fluxes during the periods before 11.3, 8.8–7.8, 6–5, and 3.1–2.4 cal ka BP recorded by Greenland ice cores. Our study may document the intensity of the Siberian High in geological history. The intensity and position of the Siberian High may play an important role in the history of dust emission in arid Central Asia.

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