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A 108.83-m ice-core record of atmospheric dust deposition at Mt. Qomolangma (Everest), Central Himalaya

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ABSTRACT

The central Himalaya can be regarded as an ideal site for developing a long-term ice core dust record to reflect the environmental signals from regional to semi-hemispheric scales. Here we present a dust record from segments of a 108.83-m ice core recovered from the East Rongbuk (ER) Glacier (27°59′N, 86°55′E; 6518 m a.s.l.) on the northeast slope of Mt. Qomolangma (Everest) in the central Himalaya, covering the period AD 600–1960. Due to rapidly layer thinning and coarse sampling, we primarily discuss the changes in the dust record since AD 1500 in this paper. Results show a significant positive relationship between the dust concentration and reconstructed air temperatures during this period, suggesting a likely cold–humid and warm–dry climatic pattern in the dust source regions, namely Central Asia. This is associated with the variability in the strength of the westerlies and its corresponding precipitation.

Introduction

Mineral dust plays an important role in paleoclimate studies because it can be used as a proxy of continent aridity and changes in global wind systems. For this reason, ice core dust records are useful in deducing past changes in atmospheric circulation and climatic regime in the dust source regions (e.g., Petit et al., 1999). Eolian activities are prevalent in the arid and semi-arid environment of Central Asia, which is usually regarded as a primary source of dust storms in the world (Prospero et al., 2002). Thus, the dust storm history from those regions is crucial for understanding changes of the regional environment and atmospheric circulation. For instance, Thompson et al. (2000) suggested that the high dust-concentration events of an ice core recovered from the Dasuopu Glacier in the central Himalaya, which is about 125 km northwest away from the East Rongbuk (ER) Glacier, were consistent with historical droughts in India. By using a shallow ice core recovered from the ER Glacier, Xu et al. (2007a) found a close relationship between the dust storm activity in Central Asia and the North Atlantic Oscillation (NAO) during past ~50 yr.

Thompson et al. (2000) observed a positive relationship between the dust and $\delta^{18}O$ records (a proxy for temperature) in the Dasuopu ice core during the period AD 1440–1997, and they attributed the possible reasons to reduction in snow cover, enhanced aridity, and/or increased agricultural activity in the dust source regions. However, the mechanism behind these relationships is not well established. Here we focus on a new ice-core dust record from the ER Glacier with the goal of reconstructing the environmental change in the arid and semi-arid areas of Central Asia, and we speculate on the possible mechanisms relating dust and temperature. The term "dust" of this paper is used as a synonym for insoluble particles.

Data and methods

A 108.83-m-long ice core to bedrock was recovered in September–October 2002 on the saddle of the ER Glacier (Fig. 1). The ER Glacier covers an area of 48.45 km^2 with a length of 14 km. Repeated surveys using a Global Positioning System (GPS) in 1998 and 2002 did not identify horizontal movement at the drilling site. The high accumulation (~50 cm water equivalent/yr) and low mean annual temperature at the site result in the preservation of a high-resolution climate record (Hou et al., 2003). The ice core was maintained below −5 °C from the time of drilling until analysis.

Ice core samples were selected from segments below 26.47 m (the close-off depth of this core is at ~26.2 m (Hou et al., 2007)) down to the bottom part of the core. Each sample (~50 g) corresponds to a length of 4–10 cm and covers durations from seasonal for the upper

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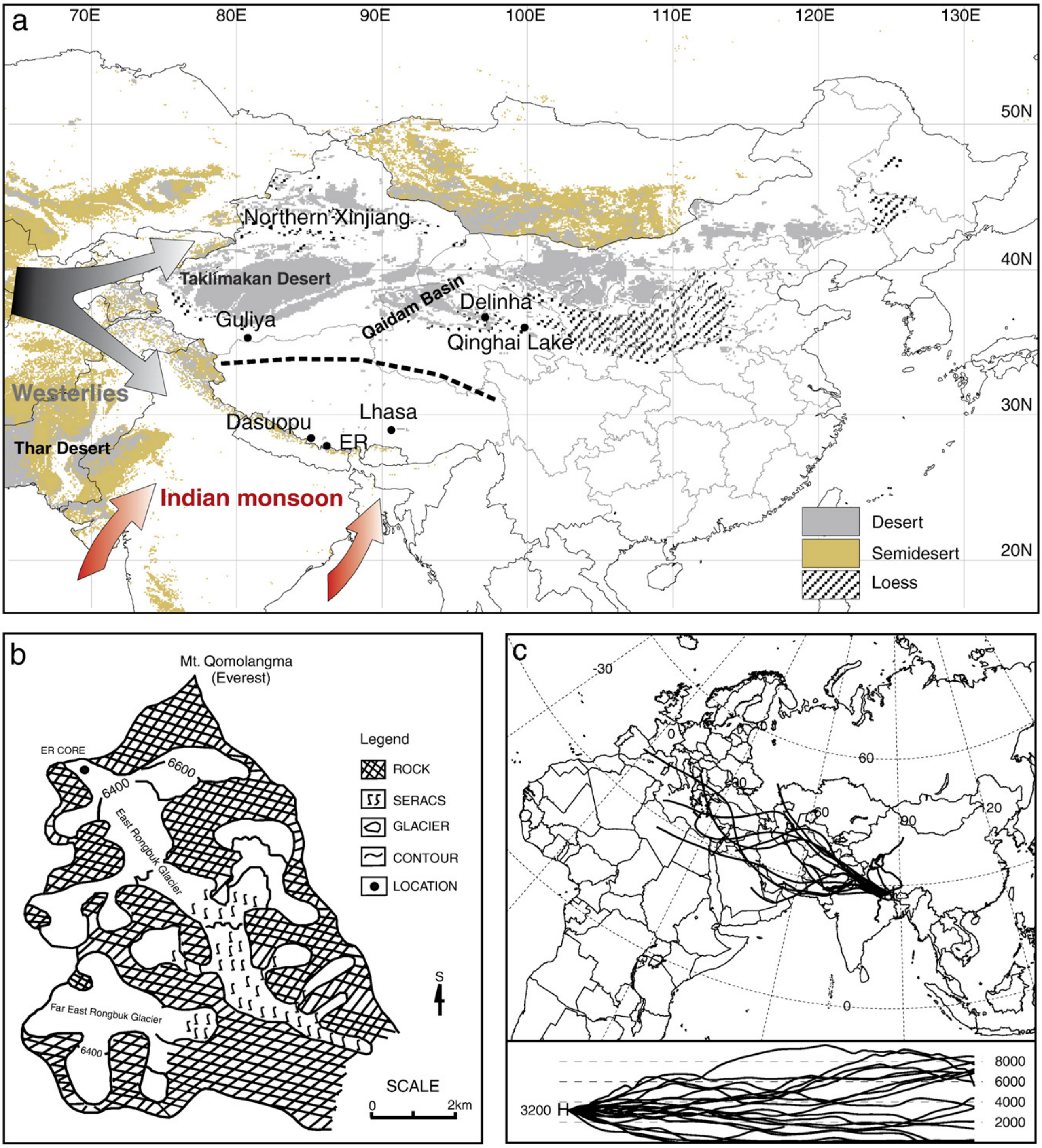

Figure 1. (a) Location map of all data sites mentioned in the text and distribution of dust sources and general patterns for winter and summer circulation systems. The dashed line represents the northern border of the Indian monsoon (34°–35°N in the middle of the plateau). (b) Map of the ER Glacier showing the ice core drilling site. (c) The 5-day air back-trajectories to the ER ice core drilling site during the periods when dust weather occurred in the northern India from April to June of 2001–2005 (Prasad and Singh, 2007).

core sections to multi-annual for the bottom sections. Ice samples were decontaminated by three repeated washings in ultra-pure water (MilliQ) in a manner similar to that of Delmonte et al. (2002), and measurements were performed using a microparticle counter (Coulter Counter Multisizer IIe ©, 256 channels) set up in the class-100 clean room of LGGE laboratory (Grenoble, France). The instrument was set to detect particles with equivalent spherical diameter from 1.0 to 30.0 μm. Each concentration and size distribution value represents the average of at least three independent measurements on the same sample. The total mass of dust has been calculated from the volume size distribution assuming an average density of 2.5 g cm^{-3}.

Subsequently, this ice core was continuously melted into 3123 samples and analyzed for soluble ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}), stable isotopes (δD and δ^{18}O), and trace elements. The ice core was annually dated to AD 1534 at 98 m using seasonal variations of stable isotopes and soluble ions, and the timescale was verified by identifying large volcanic horizons (Kaspari et al., 2007; Xu et al., 2009a). Below 98 m, annual layer counting is not possible due to layer thinning; thus prior to AD 1534 the ice core was dated using a flow model (Kaspari et al., 2008). The age of the bottom 2 m was constrained using methane and the isotopic composition of atmospheric O_2, and the results is 1498–2055 yr (Hou et al., 2004). Dating

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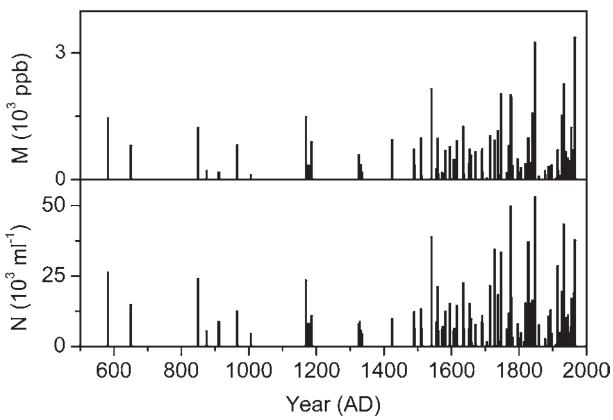

Figure 2. Profiles of dust number (N) and mass (M) in the ER ice core.

uncertainties are ±0 yr at AD 1963 and ±5 yr at AD 1534. More details can be found in Kaspari et al. (2007, 2008).

Results and discussion

Dust variability over past five centuries

A total of 167 samples were analyzed and these samples cover the period AD 600–1960. It is worth pointing out that, due to rapidly layer thinning and coarsely sampling, samples older than AD 1500 are sparse (less than 2 samples per 100 yr). The mean number and mass concentrations of dust with d>1 μm are 8801.5 (±738.0) ml^{-1} and 465.8 (±43.5) ppb, respectively (Fig. 2). In Table 1, we compared our results with those from the polar regions and the other Tibetan Plateau (TP) sites. It is apparent that the number and mass concentrations of the ER core are quite comparable with that from Canadian Arctic (Fisher and Koerner, 1981; Koerner and Fisher, 1982; Zdanowicz et al., 1998), or Antarctic and Greenland ice cores during the last glacial maximum (LGM) (Delmonte et al. 2002; Steffensen, 1997), but higher than that from Antarctic and Greenland ice cores during the Holocene or modern time (Steffensen, 1997; Hammer et al., 1985; Murozumi et al., 1969; Kumai, 1977; Steffensen, 1988; Xu et al., 2007b). However, our results are an order of magnitude lower than those measured in the snow and ice from the central and western TP (Wake et al., 1994).

Two representative segments, AD 1815–1825 corresponding to the period of lowest dust concentration and AD 1690–1730 corresponding to the period of highest dust concentration, are shown in Figure 3. Grain-size distributions are fitted very well with a log-normal curve, especially for the fine particles. The single modal distribution in the two segments implies only one primary source area, namely the vast arid and semi-arid regions of Central Asia (Wake et al., 1993). The modes are 3.2 μm and 4.2 μm, respectively, which are typical of particles deposited in alpine snowfields after long-distance transport (Wake et al., 1994; Osada et al., 2004; Zdanowicz et al., 2006) and are much larger than those of polar ice cores (~2 μm) (Xu et al., 2007b; Delmonte et al., 2002; Steffensen, 1997). From the shape of the size distribution, a distinguishing characteristic is the deviated fitting of the coarse particles (>10 μm), which likely come from the local areas, including the exposed rock walls of the glacier basin, as well as extensive glaciofluvial deposits downstream (Wake et al., 2004; Xu et al., 2009b). If we attribute the particles with d>10 μm to local sources, then their contribution to dust number is less than 1% (albeit more than 30% by mass concentration), suggesting that the influence of local source to the dust number concentration is negligible. Due to this minor influence and scanty samples, we primarily discuss the change of dust number concentration since AD 1500 in the following content.

The 10-yr averages of dust and Ca^{2+} (both have been used as proxies for change in the aeolian dust cycle (Legrand and Mayewski, 1997)) show a similar change, albeit with varied amplitude (Figs. 4a and b). Intervals around 16th, 18th, mid-19th, and post-20th century are characterized by relatively high dust concentration. In comparison with reconstructed temperatures from southern TP (Wu and Lin, 1981) (Fig. 4c), all of China (Yang et al., 2002) (Fig. 4d) and Northern Hemisphere (Mann et al., 1999) (Fig. 4e), the striking features are periods of low dust concentration corresponding to cold phases and high dust concentration corresponding to warm phases. The dust concentration shows a clear positive correlation with temperature reconstructed from southern TP because both are from the same

Table 1
Atmospheric dust concentrations in the snow and ice samples from the polar and TP sites.

	Latitude	Longitude	Elevation (m a.s.l.)	Period[a] (yr AD)	Analytical method[b]	Size range (μm)	Number (×10^3) ml^{-1}	Mass (μg kg^{-1})*	Reference
East Rongbuk (Himalaya)	27°59′N	86°55′E	6518	Past 1400 yr	CC	1–30 μm	8.8	466	This paper
Mt. Geladandong (TP)	33°24′N	91°06′E	5950	1988–1990	CC	>1 μm	165.3	2630	Wake et al. (1994)
Chongce Glacier (TP)	35°12′N	81°06′E	6327	1980–1987	CC	>1 μm	616	8220	
Dunde Ice Cap (TP)	38°06′N;	96°24′E	5325	1981–1986	CC	>2 μm	80.4	nd	
Canadian Arctic									
Penny Ice Cap	67°15′N	66°45′W	1980	1988–1994	CC	0.65–12	31.6	143	Zdanowicz et al. (1998)
						1–12	13.7	129	
Agassiz Ice Cap	80°42′N	73°06′W	1600	1950–1977	CC	>1	18.3	n/a	Koerner and Fisher (1982)
				Last 5000 yr	CC	>1	18.2	n/a	
Devon Ice Cap	77°N	82°W	1800	Last 7000 yr	CC	>1	8.30	235	Fisher and Koerner (1981)
Greenland									
Summit	72°35′N	37°38′W	3207	Recent snow	CC	0.5–12	n/a	46	Steffensen (1997)
				LGM		>2 μm	n/a	301	
Dye 3	65°11′N	46°11′W	2477	Last 10,000 yr	LLS	0.2–4	n/a	50	Hammer et al. (1985)
				1978–1983	LLS	0.2–4	9.4	n/a	
				1780–1951	LLS	0.2–4	20.0	n/a	
Camp Century	77°10′N	61°08′W	1885	Recent snow	CHEM	n/a	n/a	35	Murozumi et al. (1969)
				1753–1965	EM	0.02–8	n/a	35	Kumai (1977)
Sites A and D (average)	70°N	39°W	3070	1891–1910	LLS	0.2–4	n/a	74	Steffensen (1988)
Inland sites (average)			>2400	1940–1950	LLS	>1	14	n/a	Hammer (1977)
Antarctica									
Dome C	75°06′S	123°24′E	3233	LGM	CC	0.7–20 μm	195	790	Delmonte et al. (2002)
Dome A	80°22′S	77°22′E	4093	Mid-Holocene	CC	>0.7	2.93	8.1	Xu et al. (2007a)

n/a means not available.
[a] Period of snow accumulation represented by the data.
[b] Analytical methods: CC, Coulter counter or equivalent method; CHEM, calculated from chemical data (typically [Al], [Ca], or [Si]); EM, electron microscope; FLTR, based on dry filter weights; LLS, laser light scattering.

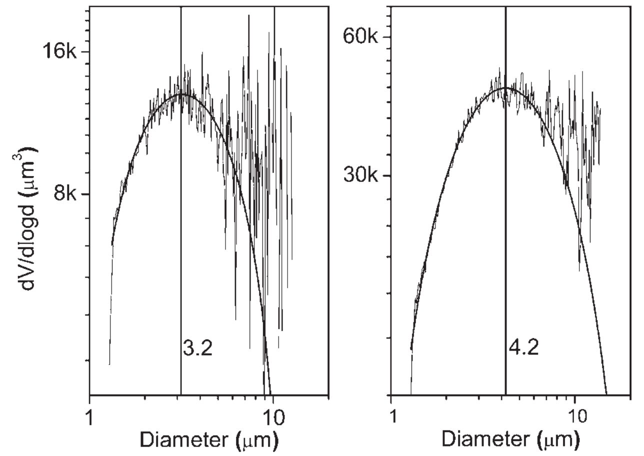

Figure 3. Examples of a log-normal curve fitted to volume distributions of dust particles from the ER ice core samples. Each example represents an interval of more than 5 samples.

climate domain. An inverse relationship between temperature from southern TP and ER ice-core accumulation (Fig. 4f) is observed, which is also observed for the Dasuopu ice core. As to the Dasuopu core, annual averages of dust are positively correlated with $\delta^{18}O$ during the period AD 1440–1997 ($r^2 = 0.25$, $P < 0.01$, $n = 558$) (Thompson et al., 2000), and a negative relationship exists between the annual accumulation and Northern Hemisphere temperature ($r^2 = -0.22$, $P < 0.05$, $n = 295$) during the period AD 1700–1995 (Duan et al., 2006). While some differences exist between accumulation records in Dasuopu and ER ice cores (Kaspari et al., 2008), similar dust origins suggest a likely cold–humid and warm–dry climate pattern in the arid and semi-arid regions of Central Asia during past five centuries.

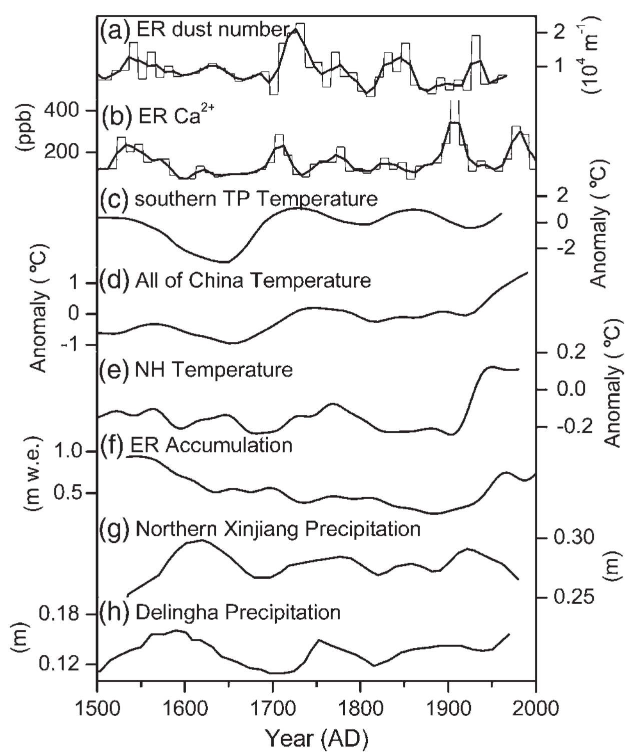

Figure 4. Profiles of 10-yr averages of (a) dust number, (b) Ca^{2+}, and (f) accumulation in the ER ice core. The thick lines represent the 31-yr running mean. Regional to hemispheric temperature variations from (c) southern TP (Wu and Lin, 1981), (d) all of China (Yang et al., 2002), and (e) the Northern Hemisphere (NH) (Mann et al., 1999). Reconstructed precipitation based on tree rings from (g) northern Xinjiang (Yuan and Han, 1991) and (h) Delingha (Shao et al., 2005).

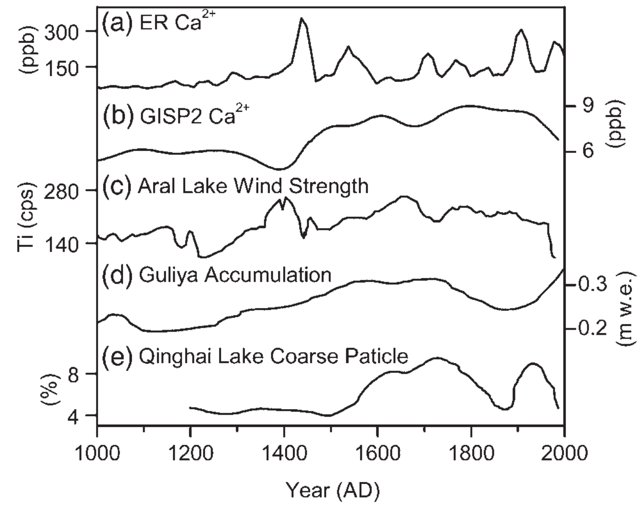

Figure 5. Profiles of 31-yr running mean Ca^{2+} of (a) the ER ice core and (b) the GISP2 ice core from Greenland (Mayewski et al., 1997). (c) Reconstructed wind strength and frequency from record of titanium in Large Aral Sea sediments of western Central Asia (Sorrel et al., 2007). (d) Accumulation record of the Guliya ice core from the northwest TP (Yao et al., 1996). (e) Precipitation variations in the northeast TP deduced from coarse particle (>63 μm) of a sediment core from the Qinghai Lake (Zhang et al., 2003).

Other evidence from the TP and northwest China support our results. For instance, tree ring-based precipitation reconstructions show that precipitation in northwest China is inversely and significantly correlated with air temperature (Yuan and Han, 1991; Shao et al., 2005) (Figs. 4g and h). Grain-size variations of magnetic particles from Chen Co Lake in southern TP indicated a cold–humid and warm–dry climate pattern since the Little Ice Age (LIA) (Zhu et al., 2003). Fluctuations of glaciers in the Himalaya and especially on the TP indicate that periods of glacier advance during the LIA coincided with cold periods (Yang et al., 2007). Recently, using records of retreating glaciers, increasing temperature and decreasing precipitation, a warm–dry climate has been found in the central Himalaya during the recent decades (Ren et al., 2004, 2006).

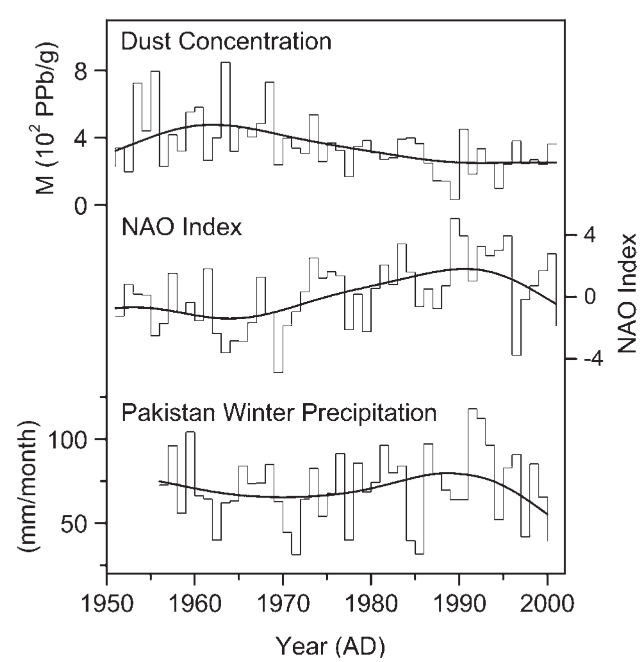

Figure 6. Comparisons of dust record from the 40-m ER ice core (Xu et al., 2007a), the winter (DJFM) NAO index (Hurrell, 1995) and Pakistan winter (DJFM) precipitation (Syed et al., 2006). The solid thick lines represent the 11-yr running mean.

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The climate in the central Himalayan region is dominated by the westerlies in the winter half year and Indian monsoon in the summer half year (Ye and Gao, 1979). Dust storm activity on the TP occurs principally between December and June, moving gradually northwards as the season progresses. This seasonal movement is closely related to the movement of the westerly jet center on the TP (Fang et al., 2004). During the winter, the westerly jet strengthens and shifts to south of the Himalaya, and TP climate is primarily influenced by continental air masses originating over Central Asia. Figure 1c shows the 5-day air back-trajectories to the ER ice core drilling site during the periods when dust weather occurred in the northern India from April to June of 2001–2005 (Prasad and Singh, 2007). It is clear that the air mass moves first through northwestern India before arriving at the central Himalayan region, implying that dust in the central Himalaya can be possibly transported from northwestern India under a suitable dust weather condition (Xu et al., 2009b).

During the past five centuries, and especially during the LIA, the westerly jet may have been intensified due to increasing meridional contrasts in air temperature (Kuang and Zhang, 2005). This resulted in high concentrations of dust and Ca^{2+} in the ER ice core (Fig. 5a), similar to that found in the GISP2 ice core from the summit of Greenland (Fig. 5b) (Mayewski et al., 1997). A high-resolution record of titanium from a sediment core retrieved in the Aral Sea has also been interpreted as documenting an increase in the intensity of westerlies during the LIA (Fig. 5c) (Sorrel et al., 2007). The intensified westerlies increased precipitation during the winter and spring seasons in Central Asia. For instance, the increased accumulation in the Guliya ice core from the northwest TP reflects this change during the LIA (Yao et al., 1996) (Fig. 5d). Increased grain size of terrestrial debris in Qinghai Lake sediments suggests increased precipitation and river runoff feeding the lake (Zhang et al., 2003) (Fig. 5e). Lake levels such as Aral and Caspian seas in Central Asia rose and/or stabilized during the LIA, suggesting a humid LIA climate (Hoogendoorn et al., 2005; Boomer et al., 2000).

From this evidence, we conclude that the high background dust concentrations likely resulted from enhanced westerlies during the LIA. The enhanced westerlies produced higher than normal precipitation and large seasonal snow cover in Central Asia in winter and spring seasons, thus reducing dust concentration. However, during the relatively warm periods of the LIA, the intensity of westerlies weakened, resulting in low precipitation and reduced seasonal snow cover in winter and spring seasons. As a consequence, the dust concentration increased. Because precipitation mainly occurs during the summer monsoon season in the central Himalaya, there is no correspondence between dust concentration and accumulation in the ER ice core. The low accumulation during the LIA reflects a reduction in northward incursions of the Indian monsoon (Kaspari et al., 2007).

Modern analogue for elucidating past dust variability

In order to validate our assumptions, we examined the relationships over the period 1951-2001 between the high-resolution dust concentration record in the 40-m ice core recovered from the ER glacier (Xu et al., 2007a), winter (DJFM) precipitation from 26 meteorological stations distributed throughout Pakistan (Syed et al., 2006) and winter (DJFM) North Atlantic Oscillation (NAO), which may be used as an index of the westerly strength (Hurrell, 1995). The results show a significant inverse correlation between westerly strength (NAO) and dust concentrations ($r^2 = -0.46$, $P < 0.01$, $n = 51$) (Fig. 6), suggesting that westerlies may play an important role in controlling Himalayan ice-core dust concentration. Although variations in precipitation are not distinctly correlated with dust concentrations and NAO, low (high) precipitation is in phase with high (low) dust concentrations and low (high) NAO index values, suggesting that precipitation during winter may be another factor controlling the dust storm activity in Central Asia.

Conclusions

This study presents the variations of aeolian dust variability in the arid and semi-arid regions of Central Asia during past five centuries from a new Himalayan ice core. Intervals around 16th, 18th, mid-19th, and post-20th century are characteristic of relatively high dust concentrations. During the LIA, dust accumulation was positively correlated with reconstructed temperatures. A conceptual model relating to the variability of westerlies and corresponding winter precipitation was then used to explain this relationship. During cold periods of LIA, the westerlies were enhanced, resulting in higher than normal precipitation and increased seasonal snow cover in Central Asia, thus decreasing dust concentrations. During the relatively warm periods of LIA, the intensity of westerlies weakened, resulting in low precipitation in the winter and spring seasons and significantly reduced seasonal snow cover. As a consequence, dust concentrations increased.

The changes of precipitation and temperature in the arid and semi-arid region of Central Asia have different characteristics at varied spatial and temporal scales (Chen et al., 2008; Shi et al., 1994, 2006). We suggest that further studies are needed to document and fully understand the spatial and temporal patterns of precipitation and temperature changes in Central Asia. Additional sites should be used to further test our out-of-phase hypothesis of dust and precipitation changes. In addition, climate simulations would be useful in testing the relative importance of competing forcing factors under different boundary conditions in and around Central Asia.

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