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Dust storm frequency and its relation to climate changes in Northern China during the past 1000 years

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Abstract

Dust storm events and their relation to climate changes in Northern China during the past 1000 years were analyzed by using different paleoclimate archives such as ice cores, tree rings, and historical documents. The results show that in the semiarid region, the temperature and precipitation series were significantly negatively correlated to the dust storm frequency on a decadal timescale. Compared with temperature changes, however, there was a closer correlation between precipitation changes and dust storm events on a centennial timescale. At this timescale, precipitation accounts for 40% of the variance of dust fall variations during the last 1700 years, inferring precipitation control on the formation of dust storms. In the western arid region, both temperature and precipitation changes are important forcing factors for the occurrence of dust storms in the region on a centennial timescale. In the eastern arid region, the relationship between dust storm events and climate changes are similar like in the semiarid region. As a result, the effects of climate change on dust storm events were manifested on decadal and centennial timescales during the last millennium. However, there is a phase shift in the relation between climate change and the dust storm frequency. A 1400 years reconstruction of the strength of the Siberian High reveals that long-term variations of spring Siberian High intensity might provide a background for the dynamic conditions for the frequency of historical dust storm events in Northern China.

Keywords: Climate change; Dust storm; Northern China; Past 1000 years

1. Introduction

Dust storms are a kind of severe natural disaster that frequently occurs in the arid and semiarid regions of Northern China. Based on the definition of the National Weather Bureau of China (1979), dust storms are the severest of three different dust weather events (floating dust, blowing dust, and

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dust storm). Dust storms not only occur in the areas of dust origin, but the dust is also transported over large distances (Sun et al., 2001; Zhao and Zhao, 2006). Dust storms mainly occur during the spring season with a frequency maximum in April. They cause serious environmental consequences and have negative effects for human society in China and other parts of Asia, such as in Japan and Korea (Chun et al., 2002; Shao and Dong, 2006). For example, an extremely severe dust storm that happened on 5 May 1993 in northwest China caused huge calamities to human life and property with estimated economic loss of 56 billion RMB (Yang and Wang, 1993). Therefore, dust storms are an important environmental problem and receive increasing attention by the government and by the public.

In China, many studies were conducted on the temporal and spatial characteristics and transport process of dust storm events, and on their relationship to climate change based on meteorological observations over the last 50 years (Littmann, 1991; Qian et al., 2002; Wang et al., 2005; Zhang et al., 1997). However, only few studies analyze the frequency of dust storm events in relation to air temperature and precipitation changes from a long-term perspective (Zhang, 1984; Yao, 1997). Recent high-resolution paleoclimatic and paleoenvironmental reconstructions from China that cover the last millennium or more (Ge et al., 2007; Mosley-Thompson et al., 1993; Shao et al., 2005; Yang et al., 2002; Yao et al., 1996; Zhang, 1982, 1984) provide the opportunity to examine the climate/dust storm relationship. In this study, we attempt to explore the effect of climate change on the occurrence of dust storms on decadal to centennial timescales to provide a useful reference for the prediction of dust storm occurrence in the future.

2. Study area and data sources

The study area comprises the arid and semiarid regions of Northern China (Fig. 1). According to fuzzy cluster analysis of annual precipitation records, the arid region can be subdivided into a western arid region and an eastern arid region (Xu et al., 1997).

2.1. The western arid region

In this region, available high-resolution proxy data include the microparticle concentrations, net glacial accumulation of the Guliya ice core-2 record (35°17′N, 80°29′E, 6200 m) and a tree-ring width chronology from Tien Shan (40°N, 72°30′E; Fig. 2). The microparticle concentration series was established by Thompson et al. (1995). Microparticle concentration is defined here as the number of particles per unit volume of melted ice, which is the preferred method of presenting dust data in much of the scientific literature on ice-core records (Davis et al., 2005; Mosley-Thompson et al., 1993; Davis and Thompson, 2006).

The timescale of the Guliya ice core-2 was established by counting visible annual dust layers, which guaranteed the accuracy of chronology and allowed the reconstruction of net accumulation rates of snow for the last two millennia (Thompson et al., 1995, 2003; Yao et al., 1996; Davis et al., 2005). Since the Guliya ice cap borders the

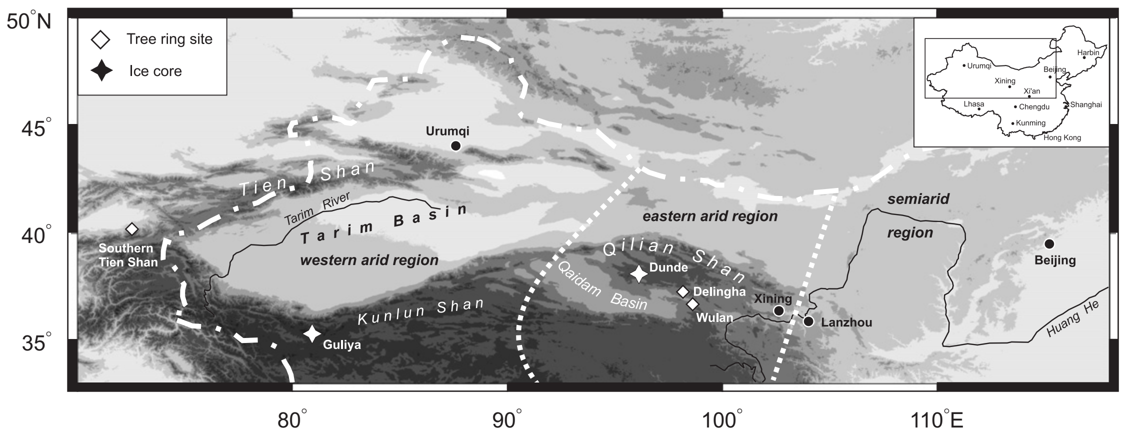

Fig. 1. Study area and location of proxy records.

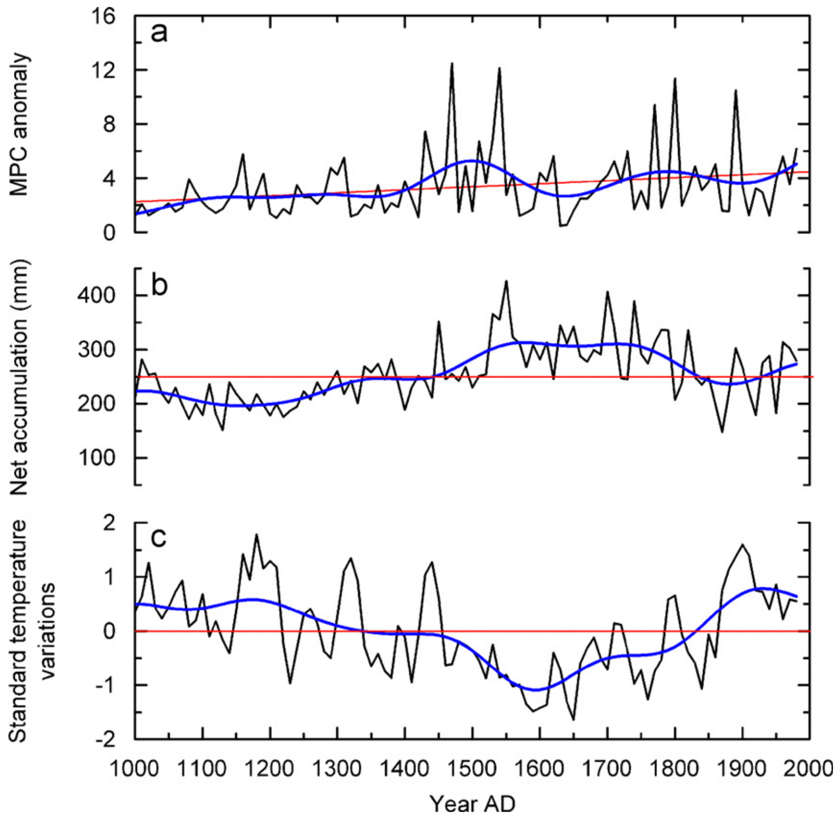

Fig. 2. The microparticle concentration (MPC) (a), net accumulation (b) recorded by Guliya ice core, and the Tien Shan tree-ring width (c) during the past 1000 years. The superimposed smoothed curves are derived by 10-point FFT filtering to emphasize long-term fluctuations. Straight lines indicate linear trends.

Taklimakan Desert to the north, the Guliya ice core has a high microparticle concentration and is a good indicator of atmospheric dust concentration variations.

The variations of the Guliya ice-core accumulation record correlate closely ($r = 0.55$, $p < 0.01$) with standardized precipitation deviations from the Xinjiang region that had been smoothed with a 3 year running mean (Yang et al., 2004). It was concluded that the net accumulation rate in the Guliya ice core represents variations of annual rainfall in the western arid region, which is confirmed by Yang et al. (2007).

The Tien Shan tree-ring width chronology was derived by long-living juniper trees and covers the last 1000 years. Low-frequency components were retained in the final index chronology by calculating differences between the original measurements of 51 ring width series with lengths >500 years and their long-term means (for details see Esper et al., 2003). Correlation analyses with climate data from nearby meteorological stations indicate that the ring width record represents long-term temperature variations (Esper et al., 2003). This is also confirmed by comparisons with other palaeo-temperature records from western central Asia (Yang et al., 2007).

2.2. *The eastern arid region*

In the eastern arid region, available proxy data include the microparticle concentration recorded in Dunde ice core (38°06′N, 96°24′E), precipitation series reconstructed from tree-ring widths of *Juniperus przewalskii*, and a mean annual temperature reconstruction covering whole China (Table 1; Fig. 3). Mosley-Thompson et al. (1993) reconstructed a microparticle concentration series from the Dunde ice core in the Qilian Mountains for the last 1000 years. The timescale for the youngest 380 a was established based on counting visible annual dust layers, while for the older part the timescale is based on a model-based time–depth relationship (Lin et al., 1995). Details of the ice-core analysis are described by Thompson et al. (1989),

Table 1
Characteristics of proxy data series in the arid and semiarid zones of Northern China

Site no.	Proxy series	Proxy type	Parameter	Representative region	Time resolution	Source
1	Guliya ice core	Microparticle concentration and net accumulation	Atmospheric dust concentration and precipitation	Western arid region	Decadal	Thompson et al. (1995); Yao (1997)
2	Tien Shan	Tree-ring widths	Annual air temperature	Western arid region	Annual	Esper et al. (2003)
3	Dunde ice core	Microparticle concentration	Atmospheric dust concentration	Eastern arid region	Decadal	Mosley-Thompson et al. (1993)
4	Delingha and Wulan	Tree-ring widths	Annual precipitation	Eastern arid region	Annual	Shao et al. (2005)
5	China temperature composite	Multi-proxy reconstruction	Annual air temperature	Whole China	Decadal	Yang et al. (2002)
6	Food/drought index for Haihe River basin	Historical documents	Annual precipitation	Semiarid region	Decadal	Yan et al. (1993)
7	Dust fall record	Historical documents	Atmospheric dust concentration	Semiarid region	Decadal	Zhang (1982, 1984)

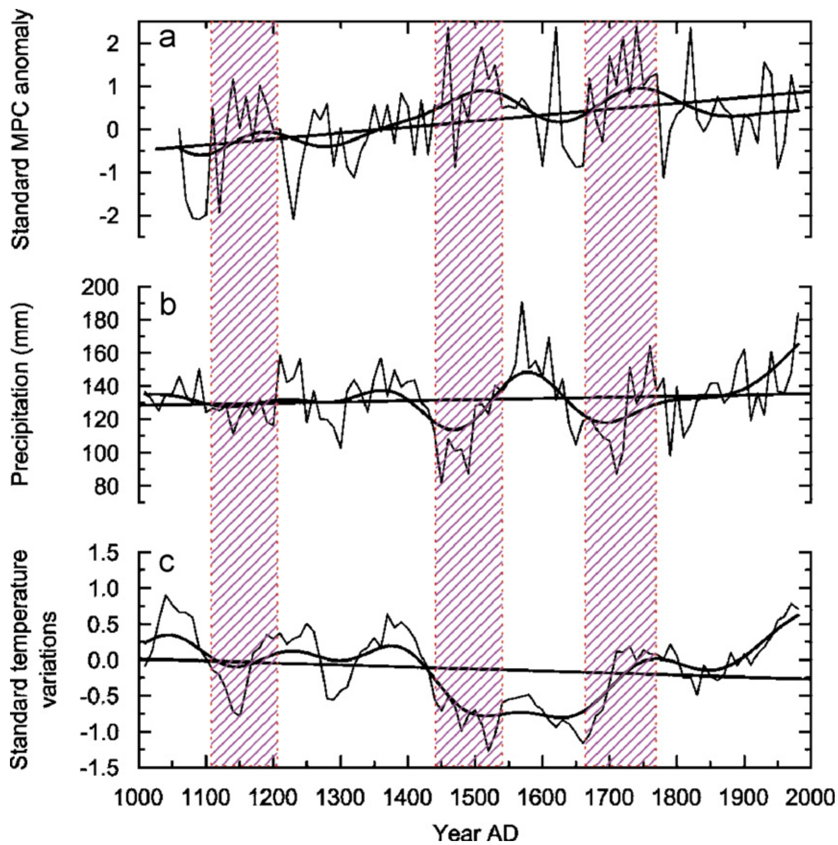

Fig. 3. Comparison of the microparticle concentration (MPC) in Dunde ice core (a), reconstructed precipitation series from Delingha and Wulan tree-ring widths (b) and China temperature reconstruction (c) during the past 1000 years. The smoothed curves, straight lines are same as Fig. 2. Broad shaded vertical bars indicate three periods of maximum dust storm frequency.

Mosley-Thompson et al. (1993), and Lin et al. (1995). Since the Dunde ice cap is in a geographical environment surrounded by desert and Gobi and located at a relatively low altitude of 5325 m, the Dunde ice core has a higher microparticle concentration than the Guliya ice core. Hence, the microparticle concentration in the Dunde ice core is used as a dust storm indicator for this region (Yang et al., 2006).

By using a well-replicated tree-ring width chronology from the Delingha and Wulan regions (Qinghai Province), Shao et al. (2005) developed a reconstruction of annual precipitation (for the period from previous July to current June) for the last 1000 years. The reconstruction accounts for 65% of the variance in the calibration period 1955–2002 and is able to document both low- and high-frequency precipitation variations of the region very well.

Temperature variations in the eastern arid region are represented by a decadal temperature reconstruction for whole China (Yang et al., 2002). This reconstruction has a high time resolution and shows a very high correlation ($r = 0.60$, $p<0.01$) to an annual temperature composite with 50-year resolution for this region (Yang et al., 2003) during the last 1000 years. The China temperature composite was established by combining multiple paleoclimate proxy records from ice cores, tree rings, lake sediments and historical documents.

2.3. The semiarid region

Proxy data in the semiarid region include a flood/drought index in the Haihe River basin which is a large basin southeast of Beijing, a temperature reconstruction for whole China and a regional dust fall series reconstructed from historical records (Fig. 4) that are not related to a single location. All these records have a decadal time resolution. According to Yan et al. (1993), the decadal flood/drought index series for the Haihe River basin was defined by the equation $\alpha = F/(F+D)$, where F and D are the numbers of reported serious flood and drought events during a decadal interval. The decadal-scale correlation between the flood/drought index series with a moisture index series by Gong and Hameed (1991) is 0.45 ($p<0.01$). The two series also agree well in low-frequency variations. The moisture index was established by the equation $I = 2F/(F+D)$, where F and D were derived from historical documents and averaged over 5-year periods.

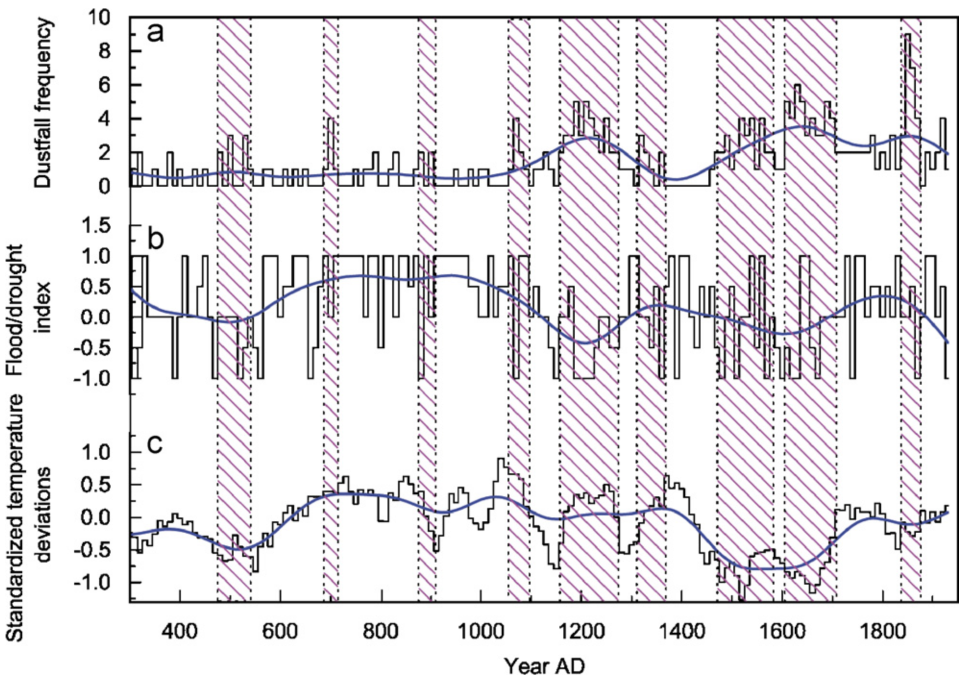

Fig. 4. Comparison of dust storm frequency in Northern China (a), flood/drought index record in Haihe River basin (b), and China temperature reconstruction (c). Vertical bars indicate periods of enhanced dust storm frequency. The smoothed curves, straight lines and broad shaded vertical bars are same as Fig. 3.

Dust fall events in historical times (a total of 1156 records) were compiled by extracting reports in official chronicles, local chronicles and personal diaries (Zhang, 1982, 1984). Dust storm events in Chinese historical documents were generally described as "dust rain (fall)", "dust haze" and "yellow fog", which correspond to the categories of serious dust storms and floating dust in modern meteorological records. They can occur several times in a year, and each dust fall event covered a large area over several Chinese provinces and usually had duration of 2 days. According to Zhang (1982), a year with dust fall occurrences was defined as "dust fall year". It is noteworthy that dust falls resulting from tephra and local dust storms were excluded from the final dust fall record. The decadal dust fall series was derived by counting the number of "dust fall years" in each decade. Since about 80% of all historical dust fall events occurred in the semiarid region, the decadal dust fall series represents the variation of dust storm events in the semiarid region during the past 1700 years. Recently, Deng and Jiang (2005) established an annually resolved dust series for North China for the period 1463–1913 based on 1401 records of dust occurrences collected from official and local chronicles. We computed the correlation of the decadally averaged dust series developed by Zhang (1982) and Deng and Jiang (2005) during the common period 1463–1913. The correlation is 0.44 ($n = 45$, $p < 0.01$), thus confirming that the dust fall series of Zhang (1982) is a reliable proxy for the variation of dust storm events.

To represent temperature variations in the semiarid region, we use a reconstructed temperature composite for whole China (Yang et al., 2002). This is justified since it shows a high correlation over the last 1200 years ($r = 0.73$, $p < 0.001$) with an annual temperature reconstruction for eastern China. The latter was derived from historical documents and has a 50-year resolution (Wang et al., 2001).

2.4. Methods

In order to analyze the influences of temperature and precipitation on dust events, we computed their correlation coefficients on decadal and centennial timescales (Table 2). The latter was derived after smoothing the original time series with an 11-point running mean. The smoothed time series show a high autocorrelation. Therefore, the significance of the correlation was determined by a student's *t*-test after adjusting the degrees of freedom for autocorrelation (Schönwiese, 2000).

3. Dust storm events and climate changes in different regions

3.1. Dust storm events and their relation to climate in the western arid region

Fig. 2 shows the temperature, precipitation, and atmospheric dust changes in the western arid region over the past 1000 years represented by the Tien Shan tree-ring chronology, the ice accumulation and the microparticle concentration in the Guliya ice core, respectively. Temperature displays low-frequency trends, such as the warm periods during the 11–12th centuries and during the 20th century, and the cool periods in the 15–19th centuries. For

Table 2
Correlation of temperature, precipitation, and dust storm index in different regions during the last millennium

Correlation coefficient	Dust storm index		
	Western arid region Microparticle concentration in Guliya ice core	Eastern arid region Microparticle concentration in Dunde ice core	Semiarid region Dust storm records in historical records
Temperature index			
R1	0.01	−0.15	−0.22 ($p<0.01$)
R2	−0.32 ($p<0.05$)	−0.51 ($p<0.01$)	−0.28 ($p<0.05$)
Precipitation index			
R1	0.16	−0.08	−0.27 ($p<0.01$)
R2	0.52 ($p<0.01$)	−0.22 ($p<0.05$)	−0.63 ($p<0.01$)

Note: R1 is the correlation coefficients between various original data series, which reflects the correlation at decadal timescale. R2 is the correlation of smoothed data series, which reflects the correlation at centennial timescale.

precipitation, this region witnessed a prolonged humid period from 1500 to 1820s and a long dry period from AD 1000 to 1500. The multi-decadal variations of temperature and precipitation are mostly coincident so that cold-humid and warm-dry climate patterns are dominant during the last millennium.

The microparticle concentration variations indicate an increasing trend of the atmospheric dust content. The 1430s mark a turning point, after which dust concentration increases abruptly and fluctuates greatly in amplitude. Two marked dust peak periods occurred during AD 1430–1570 and 1770–1900.

The influence of main climate parameters on dust event frequency can be derived from Table 2. The microparticle concentration variation is uncorrelated to the temperature index on a decadal time, but it is significantly negatively correlated to the temperature index on a centennial timescale. The correlations between the microparticle concentration and precipitation on decadal and centennial timescales are positive. This implies that both temperature and precipitation changes are important forcing factors for the occurrence of dust storms in the region on a centennial timescale. These conclusions remain consistent if we regard dust flux as a proxy of atmospheric dust instead of dust concentration. Since net accumulation of the Guliya ice core was reconstructed, we were able to obtain a dust flux series by multiplying the net accumulation with dust concentration. We computed the correlation between the dust flux series and temperature and precipitation indices in this region. The correlation coefficients are −0.1 and 0.4 at decadal timescale, whereas they are −0.56 and 0.73, respectively, at centennial timescale.

3.2. *Dust storm events and their relation to climate in the eastern arid region*

Fig. 3 shows temperature (the China temperature composite) and precipitation (the tree-ring widths from the Delingha and Wulan regions) variations in the eastern arid region, and the variation of dust storm events recorded by the dust particle content in the Dunde ice core. With the exception of a period during the 16th and 17th centuries, temperature and precipitation variations showed generally good agreement during the past 1000 years. The correlation coefficient of the decadal time series is 0.33 ($p<0.01$) which means that temperature was usually above/below average when wet/dry climate conditions predominated. The microparticle concentration recorded in the Dunde ice core shows an overall increasing trend. The microparticle concentration variation was basically consistent with temperature and precipitation change during the past millennium, but shows opposite sign. Three prolonged periods of high dust storm frequency during AD 1140–1220, 1430–1550, and 1680–1780 corresponded to obvious periods of cold–dry climate conditions. During warm and wet periods, the microparticle concentration in the Dunde ice core was below the average. This suggests that climate conditions might have been predominantly responsible for the frequency of dust storm events in this region.

The correlation between the China temperature composite and microparticle concentration on a decadal timescale is slightly higher than that with the precipitation index, but both of them have a low correlation coefficient (Table 2). The highest cross-correlations of −0.29 and −0.27 ($n = 93$, $p<0.01$) are found when the microparticle concentration is 30 years lagged behind the temperature and precipitation records, respectively. The correlation between precipitation and microparticle concentration on a centennial timescale improved greatly when this time lag was considered. In this case, the correlation increases to −0.45, in comparison with −0.22 for the unshifted time series (Table 2). Together with temperature, climate change accounts for 46% of the variance of dust storm variations at the century timescale during the last millennium.

The lagged correlations on decadal and centennial timescales may be explained by the delayed response of dust storm occurrence on vegetation cover changes. The latter depends on changes of temperature and precipitation conditions. According to He and Shao (2006), tree-ring width series from the Delingha region correlate significantly ($r = 0.74$, $p<0.001$) with the June–September NDVI (normalized difference vegetation index, a measurement for vegetation coverage) of grassland in the period 1982–2001. Since tree growth rates and vegetation cover in this arid region both depend on precipitation, the Delingha tree-ring width record (Fig. 3b) can also be regarded as an indicator of vegetation cover change. Therefore, it can be concluded that during cold-dry periods, low vegetation coverage offered favorable conditions for dust mobilization, which resulted in an increase of dust content in the Dunde ice core. On the opposite, vegetation coverage was high during warm-wet periods, and accordingly dust content in the ice core was low.

3.3. Dust storm events and their relation to climate in the semiarid region

Fig. 4 shows the precipitation series in the semiarid region (the flood/drought index series) and the all-China temperature series in relation to the dust storm index (dust fall events recorded in historical documents) during the past 1700 years. Periods with high dust fall frequency were AD 480–540, 690–720, 880–910, 1060–1100, 1160–1280, 1320–1370, 1470–1590, 1610–1710, and 1840–1880. The correlations between temperature and precipitation proxies on decadal and centennial timescales are 0.24 and 0.6, respectively, suggesting the predominance of warm-wet or cold-dry conditions.

All series show remarkable similarities in low-frequency variations. The nine periods of dust peaks (shaded bars) match well with phases of low precipitation, indicated by the flood/drought index record (Fig. 4). In most cases, the phases of dust peaks also correspond to phases of low temperatures. Exceptions are the periods around AD 700, 1050–1100, and 1160–1290. However, these periods coincide with pronounced minima in the flood/drought index and can thus be explained by distinct precipitation anomalies.

The correlation coefficients between the precipitation and temperature records and the dust fall record are all significantly negative on decadal and centennial timescales (Table 2). However, we found a closer relation between the precipitation and dust fall records than between temperature and dust fall on a century timescale. At this timescale, precipitation accounts for 40% of the variance of dust fall variations during the last 1700 years. These results indicate that long-term precipitation changes had a more important effect on dust occurrences relative to temperature change in this region.

Here we want to pay special attention to the period AD 1160–1290, when the dust storm frequency reached a maximum. This period was warm but also very dry. It seems to be contradictory to the above conclusion that cold climate conditions are more prone to high dust storm occurrences. However, it has to be considered that intensive human activity might also have exerted an effect on dust storm frequency in historic times. According to Zhang (2005), large-scale land reclamation occurred in the Hexi Corridor of northwest China in the 11–12th centuries. These cultivated land areas were abandoned again during the period from late 12th century to early 13th century due to frequent wars and population migrations. This resulted in accelerated farmland desertification and the occurrences of dust storm events in Northern China and even in southern China during the warm 13th century.

An effect of human activity on dust storm frequency has not only to be taken into account during historical times, but also at present. Ta et al. (2006) studied the correlation between the number of days in spring with dust storms, spring wind speeds, annual total precipitation, and annual land reclamation areas in arid regions as the Tarim Basin and the Hexi Corridor. They found that the dust storm peak in Northern China in the 1950s can be assigned to a great extent to intense human reclamation activities at that time.

3.4. Dust storm events and climate changes during the past 50 years

By averaging meteorological records of four weather stations (Ruoqiang, Kashi, Hetian and Bachu) in south Xinjiang, Wei et al. (2004) established regional series of dust storm frequency, temperature and precipitation during 1954–2000 for the western arid region. The correlation between annual temperature and dust storm occurrence is -0.39, which is consistent with the analytical results of historical data on a centennial timescale. A weak negative correlation (-0.14) is found between annual precipitation and yearly dust storm frequency, which is different from the positive correlation (Table 2) on longer timescales derived from historical data.

For the eastern arid region, we chose Delingha meteorological station to compare the number of dust storm events with climate changes. Both precipitation and temperature show significant negative correlations with the dust record ($r = -0.44$ and -0.35, respectively), confirming the results found for historic times.

In the semiarid region, a series of severe dust storms was established by Zhou and Zhang (2003) who found a total of 223 documented strong dust storm events (a single dust event covers many stations) during the 1954–2002 period in Northern China. For comparison, we constructed temperature and precipitation series by averaging meteorological records of 16 weather stations in the semiarid region. Very interestingly, there is a strong agreement between the dust storm series and the mean annual precipitation record at a 1 year lag ($r = -0.32$, $p < 0.05$), whereas the correlation between dust storm and temperature is also negative ($r = -0.25$), but not significant. The strong dust storm events in modern meteorological records correspond to "dust rain" and "yellow fog" recorded in historical documents. Therefore, the causal relationship between these dust storm series and climatic factors are comparable with the relation between dust storm events and climate changes that occurred in the historic period.

4. Discussion and conclusions

The variations in dust storm occurrence revealed by the different proxy records in the western arid, the eastern arid and the semiarid regions of Northern China show that the phase, frequency and intensity of dust storms during the past 1000 years are associated with climate changes. However, the temporal variations of various proxy records and their correlation with the dust storm record differ greatly in different regions.

In the western arid region, the period around 1430s marks a period of abrupt transition from a phase of relatively weak dust storm activity to one of strong dust storm occurrence. Both temperature and precipitation change had an important effect on the occurrence of dust storms on a centennial timescale. In the semiarid region, frequency of dust storm was low under warm–wet climate conditions and high under cold-dry conditions. In the eastern arid region, there is an increasing trend in dust storm variations during the last 1000 years. The dust storm maxima during AD 1140–1220, 1430–1550, and 1680–1780 correspond to three periods of cold-dry climate conditions.

Climate changes as the background factor causing dust storms have complex physical causes. The formation of dust storms requires three conditions: a dust source, strong wind, and low ground surface coverage. The dust source depends on the large-scale distribution of transportable material, strong winds are a climate dynamical condition (driving force for dust mobilization and transport), and the surface coverage is related to spatio-temporal variations of growing conditions for the vegetation. Climate changes might have an effect on all three of these factors. Precipitation fluctuations affect the soil moisture content, the consolidation degree of surface soil particles and, before all, plant growth and the density of the vegetation coverage. When precipitation is adequate and soil moisture conditions are favorable for vegetation growth, the probability of dust storm occurrence is reduced. In periods of dry climate, soil moisture content is low and vegetation cover is poor. Consequently, surface particles are prone to mobilization and thus the probability of dust storm events increases.

This explains why highly negative correlations between the frequency of dust events and precipitation records were found in the eastern arid region and in the semiarid region where the vegetation cover is highly sensitive to precipitation. In these regions, a small change in precipitation can significantly alter the surface vegetation cover (Xu et al., 2006). In contrast, the decadal correlation between precipitation and dust frequency in the western arid region is not significant because most of the region is covered by desert and fluctuations in precipitation do not produce a significant effect on general surface characteristics.

Low-frequency climate changes such as long-term arid or cold conditions provide a background for high-frequency dust storm variations. Due to possible lags in the response of vegetation cover to climate changes, it is expected that the effect of climate change on dust storm frequency should be higher on longer timescales (multi-decadal to centennial) than on short-term timescales (annual to decadal). Accordingly, our results show that higher correlations between climate and dust storm occurrence occur on centennial timescales rather than on decadal timescales (Table 2).

The effect of air temperature on dust storm occurrence is mainly manifested by the invasion and outbreaks of cold air, which is directly linked to the enhancement of cyclogenesis (Sun et al., 2001). This increases the possibility of the occurrence of dust storms by providing the essential dynamical effect. The finding of Qian et al. (2002) corroborates that the frequency of dust storms in Northern China is strongly dependent on spring cyclone activity and its cold surge during 1954–1998. However, the western arid region is exceptional because of a low frequency of deep cyclones or circumpolar vortex over there (Qian et al., 2002).

Under cold climate conditions, the Siberian High is strongly developed and located relatively far southward. This is favorable for strengthening and outbreaks of cold air, and thereby the formation of cyclones and for the increase of dust storm frequency. On the contrary, when climate is warm, the strength of the Siberian High weakens and its position moves northwestward. This leads to fewer and weaker frontal cyclones so that the frequency of dust storm decreases. This might be one of reasons for the high correlation between dust storm and temperature at different timescales displayed in the eastern arid region and in the semiarid region.

Actually, a 1400-year-long 3-year reconstruction for the spring (MAM) Siberian High shows that the Siberian High strengthened abruptly since the early 15th century (Meeker and Mayewski, 2002). The Siberian High reconstruction was derived from the non-seasalt potassium content in an ice core from central Greenland, which was suggested to be transported to Greenland from central Asia (Meeker and Mayewski, 2002). This transition basically coincides with a change from weak to strong dust storm activity found in the microparticle concentration of the Dunde and Guliya ice cores, and in the dust fall records of the semiarid region. Periods when the Siberian High strength exceeds the long-term average are AD 1420–1570, 1615–1740, and 1790–1850. These periods correspond with the 'Little Ice Age' (LIA) period and are generally consistent with strong dust storm activity reflected by the above three proxy records.

The decadal-scale correlations of the Siberian High strength record to the Guliya and Dunde ice-core microparticle concentrations and dust fall records of the semiarid region are 0.31, 0.25, and 0.21, respectively ($p<0.05$), suggesting that the Siberian High might be one important common forcing factor linking the dust occurrence of the above three regions. The discrepancies displayed in these three proxies representing the western arid region, the eastern arid region and semiarid region might be associated with the western, northwestern, and northern routes of cold air outbreaks that blow over three different dust source regions of the Taklimakan Desert and the Gobi Deserts in Mongolia and Northern China (including the northern loess plateau), respectively (Sun et al., 2001; Sun, 2002).

The good agreement between the Guliya ice-core microparticle concentration and the Siberian High poses an interesting question: How are dust storms of the Taklimakan Desert connected with those of Greenland? Investigations of dune moving directions show that there is a convergence belt of the prevailing northwestern and northeastern near-surface winds around 35°N, 80°E in the southern Taklimakan Desert during spring (Sun et al., 2001). The Guliya ice cap is located right above this convergence belt. Thus, it could be inferred that there is a strong convective air flow in the middle and upper troposphere, which is the driving force of dust outbreaks and the vertical dust transportation. Dust from the Taklimakan Desert can be entrained to elevations >5000 m (for example, the Guliya ice cap) by strong rising airflow and then be further transported by the westerlies over large distances, and even to Greenland (Sun et al., 2001). This process might account for the good agreement between the Guliya ice-core microparticle concentration and the non-seasalt potassium content in a central Greenland ice core. On the other hand, the strong upward air flow can produce a high possibility of precipitation occurrence, which is helpful to explain the correlation between the net accumulation and microparticle concentration recorded in the Guliya ice core on a centennial time scale (Table 2). However, it needs to be pointed out that our explanation is preliminary considering the fact that presently only few proxy records are available in this region.

Beside climatic fluctuations, human land-use practices and land cover changes strongly influence the intensity and frequency of dust occurrences. In some cases, excessive human disturbance can foster the occurrence of dust storms and to some extent might bias the statistical relationship between climate change and dust storm frequency. The quantification of the human influence on dust storm frequency in prehistoric and historic times, however, needs further investigation.

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References

Chun, Y., Boo, K.O., Kim, J., Park, S.U., Lee, M., 2002. Synopsis, transport, and physical characteristics of Asian dust in Korea. Journal of Geophysical Research 106 (D16), 18461–18469.

Davis, M.E., Thompson, L.G., 2006. Andean ice core record of a Middle Holocene Mega-drought in North Africa and the Middle East. Annals of Glaciology 43, 34–41.

Davis, M.E., Thompson, L.G., Yao, T., Wang, N., 2005. Forcing of the Asian monsoon on the Tibetan Plateau: evidence from high-resolution ice core and tropical coral records. Journal of Geophysical Research 110, D04101.

Deng, H., Jiang, W.F., 2005. Temporal distribution and characteristics of the sand-dust weathers in North China Plain from 1463 to 1913. Geophysical Research 24 (3), 403–411 (in Chinese).

Esper, J., Shiyatov, S.G., Mazepa, V.S., Wilson, R.J.S., Graybill, D.A., Funkhouser, G., 2003. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. Climate Dynamics 8, 699–706.

Ge, Q., Zheng, J., Tian, Y., Wu, W., Fang, X., Fang, X., Wang, W.C., 2007. Coherence of climatic reconstruction from historical documents in China by different studies. International Journal of Climatology, in press, doi:10.1002/joc.1552.

Gong, G., Hameed, S., 1991. The variation of moisture conditions in China during the last 2000 years. International Journal of Climatology 11, 271–283.

He, J., Shao, X., 2006. Relationships between tree-ring width index and NDVI of grassland in Delingha. Chinese Science Bulletin 51 (9), 1106–1114.

Lin, P.N., Thompson, L.G., Davis, M.E., Mosley-Thompson, E., 1995. 1000 years of climate change in China: ice-core $\delta^{18}O$ evidence. Annals of Glaciology 21, 189–195.

Littmann, T., 1991. Dust storm frequency in Asia: climatic control and variability. International Journal of Climatology 11, 393–412.

Meeker, L.D., Mayewski, P.A., 2002. A 1400 year long record of atmospheric circulation over the North Atlantic and Asia. The Holocene 12 (3), 257–266.

Mosley-Thompson, E., Thompson, L.G., Dai, J., Davis, M.E., Lin, P.N., 1993. Climate of the last 500 years: high resolution ice core records. Quaternary Science Reviews 12, 419–430.

National Weather Bureau of China, 1979. Criterion of Surface Meteorological Observation. Meteorological Press, Beijing, pp. 21–27.

Qian, W., Quan, L., Shi, S., 2002. Variations of the dust storm in China and its climatic control. Journal of Climate 15 (10), 1216–1229.

Schönwiese, C.F., 2000. Praktische Statistik für Meteorologen und Geowissenschaftler. Stuttgart, 298pp.

Shao, Y., Dong, C.H., 2006. A review on East Asian dust storm climate, modelling and monitoring. Global and Planetary Change 52, 1–22.

Shao, X., Huang, L., Liu, H., Liang, E., Fang, X., Wang, L., 2005. Reconstruction of precipitation variation from tree rings in recent 1000 years in Delingha, Qinghai. Science in China (Series D) 48 (7), 939–949.

Sun, J., 2002. Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. Earth and Planetary Science Letters 203, 845–859.

Sun, J., Zhang, M., Liu, T., 2001. Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: relations to source area and climate. Journal of Geophysical Research—Atmospheres 106 (D10), 10325–10333.

Ta, W., Dong, Z., Sanzhi, C., 2006. Effect of the 1950s large-scale migration for land reclamation on spring dust storms in Northwest China. Atmospheric Environment 40 (30), 5815–5823.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Bolzan, J., Dai, J., Gundestrup, N., Yao, T., Wu, X., Xie, Z., 1989. Holocene-Late Wisconsin Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. Science 246 (4929), 474–477.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.E., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K.B., 1995. A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability. Annals of Glaciology 21, 175–181.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.N., Henderson, K., Mashiotta, T.A., 2003. Tropical glacier and ice core evidence of climate change on annual to millennial time scales. Climatic Change 59, 137–155.

Wang, S., Gong, D., Zhu, J., 2001. Twentieth-century climatic warming in China in the context of the Holocene. The Holocene 11 (3), 313–321.

Wang, S., Wang, J., Zhou, Z., Shang, K., 2005. Regional characteristics of three kinds of dust storm events in China. Atmospheric Environment 39, 509–520.

Wei, W.S., Gao, W.D., Shi, Y.G., 2004. Influence of climate and environment chance on dust storms in Xinjiang, China. Arid Land Geography 27 (2), 137–141.

Xu, G., Yao, H., Dong, A., 1997. Climate Change in Arid and Semiarid Regions of China. China Meteorological Press, Beijing, pp. 1–101 (in Chinese).

Xu, X., Levy, J.K., Lin, Z., Chen, H., 2006. An investigation of sand-dust storm events and land surface characteristics in China using NOAA NDVI data. Global and Planetary Change 52, 182–196.

Yan, Z., Li, Z., Wang, X., 1993. An analysis of decade-to century-scale climatic jumps in history. Scientia Atmospherica Sinica 17 (16), 663–672.

Yang, G., Wang, Y., 1993. The development process of 93-05-05 extremely severe sandstorm and its prevention countermeasures. Journal of Desert Research 13 (3), 68–71 (in Chinese).

Yang, B., Bräuning, A., Johnson, K.R., Shi, Y.F., 2002. General characteristics of temperature variation in China during the Last Two Millennia. Geophysical Research Letters 29 (9), 1234.

Yang, B., Bräuning, A., Shi, Y., 2003. Late Holocene temperature variations on the Tibetan plateau. Quaternary Science Reviews 22, 2335–2344.

Yang, B., Bräuning, A., Shi, Y., Chen, F., 2004. Evidence for a late Holocene warm and humid climate period and environmental characteristics in the arid zones of northwest China during 2.2–1.8 kaBP. Journal of Geophysical Research 109, D02105.

Yang, M., Yao, T., Wang, H., 2006. Microparticle content records of the Dunde ice core and dust storms in northwestern China. Journal of Asian Earth Sciences 27 (2), 223–229.

Yang, B., Bräuning, A., Wang, J.S., Dong, Z.B., Esper, J., 2007. Late Holocene climatic and environmental changes in arid central Asia. Quaternary International, 2007, in review.

Yao, T., 1997. Climatic and environmental record in the past about 2000 years from the Guliya Ice Core. Quaternary Sciences 1, 52–61 (in Chinese).

Yao, T., Thompson, L.G., Qin, D., Tian, L., Jiao, K., Yang, Z., Xie, Z., 1996. Variations in temperature and precipitation in the past 2000a on the Xizang (Tibet) Plateau-Guliya ice core record. Science in China (Series D) 39 (4), 425–433.

Zhang, D., 1982. Analysis on the phenomena of dust falls in historical times. Chinese Science Bulletin 5, 294–297 (in Chinese).

Zhang, D., 1984. Preliminary meteorological analysis on the dust fall in China since historical times. Science in China (Series B) 3, 278–288 (in Chinese).

Zhang, D., 2005. Historical records of environmental changes and agricultural development in northwest China. Advances in Climate Change Research 1 (2), 58–64 (in Chinese).

Zhang, X.Y., Arimoto, R., An, Z.S., 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. Journal of Geophysical Research 102 (D23), 28041–28047.

Zhao, L., Zhao, S., 2006. Diagnosis and simulation of a rapidly developing cyclone related to a severe dust storm in East Asia. Global and Planetary Change 52, 105–120.

Zhou, Z.J., Zhang, G.C., 2003. Typical severe dust storms in northern China during 1954–2002. Chinese Science Bulletin 48 (21), 2366–2370.