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# Variations in dust event frequency over the past century reflected by ice-core and lacustrine records in north China

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**In this paper, we analyzed the variations of dust proxies in the Dunde, Malan and Chongce ice cores from the northern Tibetan Plateau and the Hongjiannao lacustrine sediment core from north Shaanxi Province, and found that they all showed a general decrease trend over the past century. Owing to the fact that all these ice cores and lacustrine core were retrieved from the margins and/or the leeward sides of the major areas of dust events in north China, their records could suggest that the dust event frequency in north China declined over the study period. This decrease trend might be attributed to increasing precipitation and weakening westerly. However, human activities have made the areal extent of desertification expand acceleratingly in north China. This status could make it possible that dust events would occur on a large spatial scale under the future climate change, which would be a big environmental issue we shall face.**

north China, dust event frequency, climate change

The role of dust in climate system has attracted much more attention[1,2]. To better understand the causes of climate change, it is important to reconstruct the history of atmospheric dust loading. Generally, dust weather is a major process of continental dust entering the atmosphere, and the occurrences of dust events (dust storm, blowing dust, floating dust) are highly regional. Thus reconstructions of the history of dust event frequency in different areas, especially in the major dust source areas and their adjacent regions, such as the arid region in north China, are the basic works for study on the variations in atmospheric dust loading and its effects on climate and environment. Moreover, it is not clear what the major causes of recent variations of dust events in north China are, natural factors or human factors[3–7]. Meteorological observation data showed that the trends of variations in dust event frequency in most parts of north China were similar over the past several decades[8]. Therefore, investigating the causes of variations in dust event frequency in the areas with less human activities, such as in the northern Tibetan Plateau, could help us to understand the causes of variations in dust event frequency in most other areas of north China where human activities are concentrated. The study on the secular variations in dust event frequency in large parts of north China is of important significance for the prediction of dust events also. In this paper, we will analyze the variations in dust event frequency over the past century in north China using the ice-core and lacustrine records, and try to clarify the causes of the past variations of dust

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events combined with tree-ring and meteorological observation data.

## 1 Geographic locations of research sites

Most observations and analyses of dust events showed that south Xinjiang and the Hexi Corridor associated with its adjacent Alashan Plateau are the two major regions with high frequent dust events in north China[9−11]. Therefore, reconstructions of past variations in dust event frequency around these two regions and/or in their leeward sides could help us to understand the past secular trend of dust events in north China. Under this consideration, we will select the Dunde, Malan and Chongce ice cores from the northern Tibetan Plateau and the Hongjiannao lacustrine sediment core from the boundary between Shaanxi Province and Inner Mongolia (Figure 1), and analyze the records of dust proxies in these cores to reveal the variations and trend of dust events in north China over the past century.

The Chongce (35°14′N, 81°07′E), Malan (35°50′N, 90°40′E) and Dunde (38°96′N, 96°24.5′E) ice caps are located in the margin and/or the leeward side of south Xinjiang, a major region with high frequent dust events. Many ice cores were drilled from these ice caps in the 1980s and 1990s. As expected, past climatic and environmental changes have been reconstructed based on these cores[21−23]. Here, we will focus on analyses of dust records in these ice cores. The Hongjiannao Lake (39°04′—39°08′N, 109°50′—109°56′E, 60.3 $km^2$ in area, 10.5 m in the maximum depth, 8.2 m in average depth, and $4.9\times10^8 m^3$ in volume) is situated in the leeward side of the Hexi Corridor associated with its adjacent Alashan Plateau, another major region with high frequent dust events. In June of 2002 A.D., a 71.5-cm-long sediment core was retrieved from the bottom of the lake, where the depth of water was 7.5 m. Analyses of pollen, grain size, magnetism susceptibility, total organic carbon, geochemical elements, etc., were carried out along this lacustrine core in intervals of 0.5 cm[24]. Based on the age-depth relation established using $^{137}Cs$ dating results, it was found that the lacustrine sediments began around 1927 A.D., which is consistent with the age of the formation of the lake, around 1929 A.D., according to the documentary literatures[25]. Thus, the record of grain size in the core could provide some information of dust events occurring in the 20th century.

## 2 Dust proxies and their data series

Modern observations displayed that the springtime is the high frequent dust season in north China[9−11]. Usually, on a glacier, a dust layer can be formed when a dust event occurs and passes through it. As expected, the information of dust events can be preserved in glaciers, especially in the dust layers on ice caps, and we can infer dust events from those dust layers in ice cores. The visible dust layers could be easily discerned in the Malan ice core, and most of them appeared in snow/ice layers deposited in springtime. We have pointed out that the

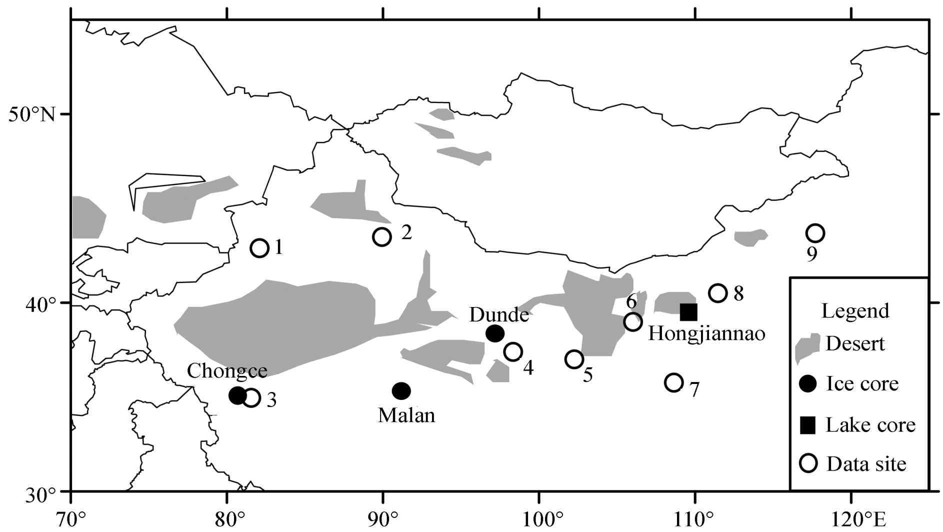


**Figure 1** Locations of the Dunde, Malan and Chongce ice cores, the Hongjiannao lacustrine sediment core, and tree-ring data sites. 1, West Tianshan tree-ring site[12]; 2, east Tianshan tree-ring site [13]; 3, Guliya ice-core site[14]; 4, Delingha tree-ring site[15]; 5, Lenglongling tree-ring site[16]; 6, Helan tree-ring site[17]; 7, Huangling tree-ring site [18]; 8, Daqingshan tree-ring site[19]; 9, Daxinganling tree-ring site[20].

ratio of dust layer thickness to ice thickness (i.e. the dust ratio) could be used as a proxy for dust event frequency in the Malan ice core, and found that the variations in the dust ratio were similar to the variations in dust events occurring in south Xingjiang over the past decades[26]. Figure 2(a) illustrates the variations in the dust ratio over the past century. A general decline trend can be clearly seen in the dust ratio variations. This indicates that the dust event frequency decreased over the study period. If the periods with a higher dust ratio than its long-range average value (about 25.5%) are regarded as the active periods of dust events while the periods with a lower dust ratio than its long-range average as the calm periods, the active periods are 1900—1915, 1925—1950 and 1960—1965 A.D., and the calm periods are 1915—1925, 1950—1960 and 1965—1999 A.D. Continental $Ca^{2+}$ concentration in ice cores is also a proxy of dust events[27,28]. Figure 2(b) presents the yearly variations in $Ca^{2+}$ concentration in Dunde ice core[29]. It is noted that the periods lasting more than 5 years with higher $Ca^{2+}$ concentration than its long-range average are 1907—1912, 1921—1926 and 1929—1940 A.D., which are accordant with the active periods of dust events reflected by the Malan ice core record. Particle concentrations in ice cores are related with frequency and strength of dust events. Because the northern Tibetan Plateau is located in the margin of the region with frequent dust events, ice cores from there contain high particle concentrations[30]. In general, peak values in particle concentrations in ice cores are very likely caused by the strong dust events, and periods with high particle concentrations might represent the active periods of dust events. Figure 2(c) depicts the variations in particle concentration in the Chonce ice core with seasonal resolution1). It indicates that the frequency and strength of dust events were more intensive before the 1940s than thereafter. If regarding the peak values above the long-range average of the particle concentrations by their two standard deviations as the consequence of the strong dust events, we can estimate the frequency of dust events by removing the peaks from the original particle concentrations data set, i.e., we can calculate the means of particle concentrations in different periods according to the new data set, and refer to the periods with higher means of particle concentrations in the ice core than the long-range average as active periods of dust events. Thereby the Chongce ice-core record exhibits that 1910—1915, 1919—1932 and 1960—1964 A.D. were the active periods of dust events. It is worthy to emphasize that the three ice-core records above indicate that dust events became less frequent over the past century (see Figure 2), and their variations were similar to those in dust event frequency observed in whole north China (data available at www.duststorm.com.cn, and see ref. [31]) over the past decades.

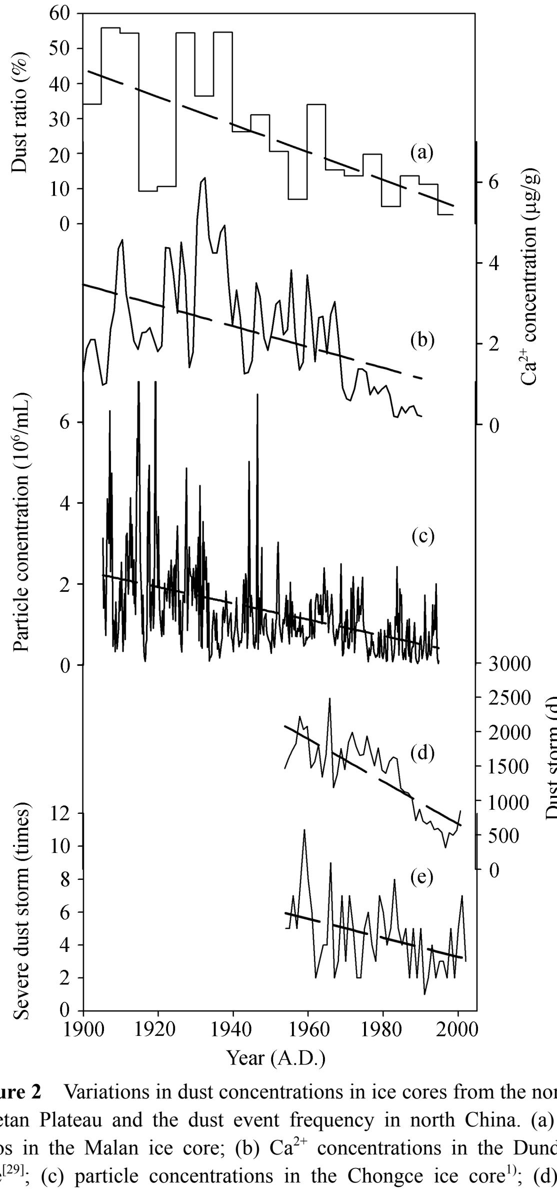


**Figure 2** Variations in dust concentrations in ice cores from the northern Tibetan Plateau and the dust event frequency in north China. (a) Dust ratios in the Malan ice core; (b) $Ca^{2+}$ concentrations in the Dunde ice core[29]; (c) particle concentrations in the Chongce ice core1); (d) dust storm frequency in China (data available at www.duststorm.com.cn); (e) strong dust storm frequency in north China[31].

1) Han J K, Nakawo M, Kumiko G, et al. Impact of fine dust air burden on the mass balance of a high mountain glacier: a case study of the Chongce ice cap, West Kunlun Mts., China. Ann Glaciol, 2006

A study[32] showed that the variations and frequency distributions of grain sizes in lacustrine sediments could provide some information of dust events, especially the variations in concentration and median diameter of coarse grain sizes could reveal the historical status of dust into lakes by wind, i.e. the historical strength and frequency of dust events. Grain size analysis of sediments in the Hongjiannao Lake was carried out using the Malvern Mastersizer 2000 laser particle size analyzer. The analytical results are displayed in Figures 3 and 4. Figure 3 clearly shows that the concentrations of coarse grain sizes (>100 μm) were much higher before the 1960s than thereafter. This implies that the strength and frequency of dust events were larger in the first half of the 20th century than in the second half. Another remarkable feature in Figure 3 is that there were peak values in concentration and median diameter of coarse grain sizes around 1936, 1939 and 1941 A.D. It was pointed out that the status of mass movement and transport into Hongjianao Lake by water stream around these periods did not change [24]. Thus these peak values likely represented increases in transport of dust by wind around those years, which coincided with peak dust concentrations in the Malan and Dunde ice cores around the 1930s. These indicate that dust events occurred frequently in north China in that period.

In general, if there are no materials which are transported into a lake basin system by wind and/or other ways except by water, the distribution of grain sizes in the lacustrine sediments is controlled mostly by the hydrodynamic regime of a lake. And in this case, the grain sizes display a gradual change from coarse near the bank to fine at the center of a lake, and their frequency curve shows a normal distribution at any site of a lake[33]. Thus, the shape of the frequency distribution of lacustrine sediment grain sizes could be used to detect if there are some other source's materials, such as atmospheric dust, moraine, etc., entering a lake. Figure 4 illustrates the frequency distributions of the grain sizes in the different sections of the Hongjiannao lacustrine sediment core. From this figure, it can be seen clearly that there are the bimodal patterns in the frequency distributions of the grain sizes in the sections of the Hongjiannao core from 42 to 48 cm (I-2 section in Figure 3) and from 65.5 to 48 cm in depth (I-1 section in Figure 3), which are corresponding to the periods of 1952 through 1960 A.D. and 1927 through 1952 A.D., respectively. The peaks

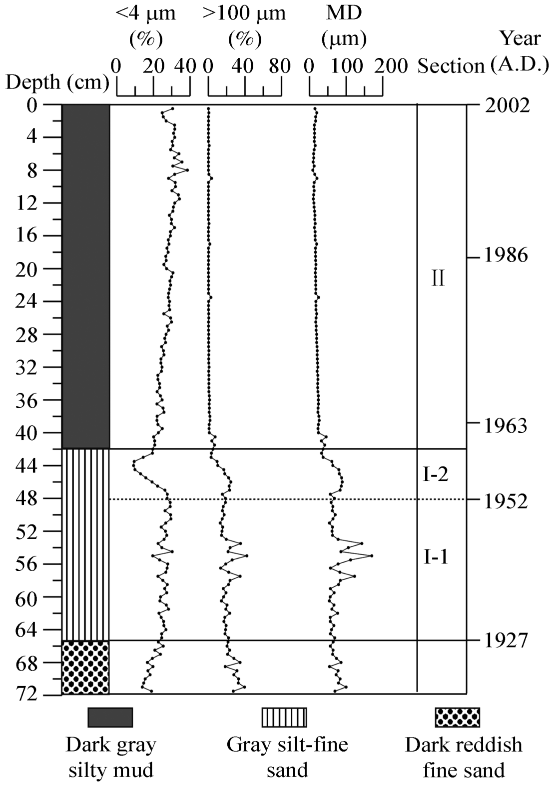


**Figure 3** Variations of lithological componets, percentages of different grain sizes and median diameter (MD) of grain sizes in the lacustrine sediment core from the Hongjiannao Lake. The lower section of the core, below 65.5 cm in depth, is dark reddish fine sand, which reflects the terrestrial environment before the formation of the lake; the section of the core from 65.5 cm to 42 cm in depth is gray silt-fine sand; the upper section of the core, above 42 cm in depth, dark gray silty mud.

appearing at the coarse grain sizes might be related with eolian dust deposits owing to the fact that there were not ice-rafted deposits and gravity flow deposits in the Hongjiannao Lake. Based on the heights of the peaks, it was speculated that eolian dust deposit flux might be larger in the period of 1927 through 1952 A.D. than in the period of 1952 through 1960 A.D. In the section of the Hongjiannao core from 0 to 42 cm in depth (II section in Figure 3), corresponding to the period of 1960 through 2002 A.D., the frequency distribution of the grain sizes just showed unimodal distribution. This suggests that eolian dust deposits might become much less, and the deposits in the Hongjiannao Lake might mostly come from fluvial silts and sands, over the past four decades. All these further indicated that dust event frequency showing a general decrease trend over the 20th century was supported by the record of grain sizes in the Hongjiannao Lake.

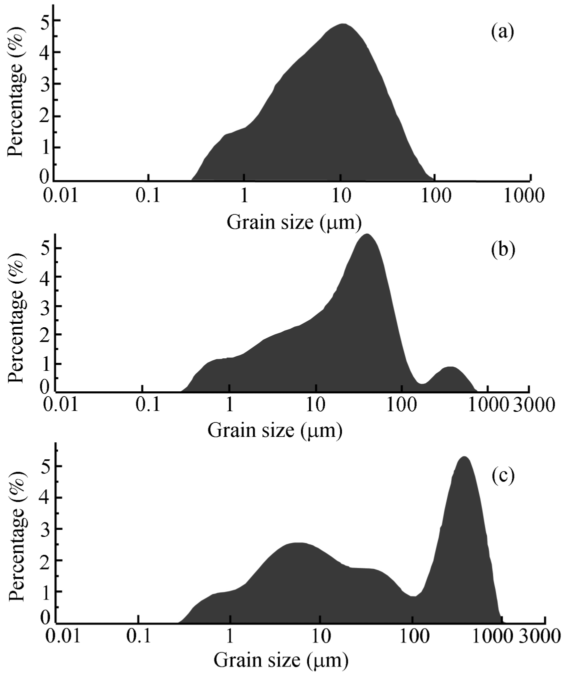


**Figure 4** The frequency distributions of the grain sizes in the different sections of the Hongjiannao lacustrine sediment core. (a) Section from 0 to 42 cm in depth (corresponding to the period of about 1960 through 2002 A.D.); (b) section from 42 to 48 cm in depth (about 1952 through 1960 A.D.); (c) section from 65.5 to 48 cm in depth (about 1927 through 1952 A.D.).

## 3 Discussion

Meteorological observation data showed that dust event frequency became less in most parts of north China over the past 50 years[8,9,11]. This fact was also reflected by the Dunde, Malan and Chongce ice-core records and the Hongjiannao lacustrine record. Thereby, the general decrease trend in dust event frequency over the 20th century recoded in the all ice cores and lacustrine core mentioned above implies that dust events in north China became less frequent over the study period to large extent.

The occurrences of dust events are closely related with the weather and land surface conditions. Wind is a major meteorological factor for dust events. Generally speaking, when surface wind weakens, the dust event frequency might decrease correspondingly. North China is mainly under the control of westerlies. The strength of westerly might become weak with the decrease in longitudinal temperature gradient caused by climate warming. This viewpoint can be confirmed by the result derived from the NCEP/NCAR reanalysis data (data available at http:/www.cdc.noaa.gov) that the average zonal surface wind speed in spring in the middle latitudes was weaker in 1980—1999 A.D. (warm period) than in 1960—1979 A.D. (cold period) (Figure 5). A recent study shows that the areal extent of shifting sand dunes in Tengger and Ulan Buh deserts and Mu Us and Horqin sands had shrunk remarkably in the past five decades[34]. This might be expected as a consequence of decreasing wind speed. Thus the decrease of westerly strength, i.e. the wind speed decrease, led by climate warming, is one important cause of the decrease trend of dust event frequency over the past 100 years.

Soil moisture regime is another important factor which influences dust emission and/or dust events. In general, when precipitation increases, soil moisture level will increase also, and consequently dust emission is restricted. Figure 6 represents the variations in precipitations at different sites in north China over the last 100 years reflected by ice core records[14,22] and tree-ring data[12,13,15−20]. It shows that even though the yearly variations in precipitations at different sites were of less comparability, the general increase trends in precipitations over the last 100 years existed at most sites in the middle and western parts of north China, but the general decrease trend just in the eastern part of north China (Figure 6(j)). Moreover, historical archive documents and meteorological observation data manifested that the climate was dry in Shaanxi, Ningxia, Gansu and Qinghai in the first half of the 20th century but wet in its second half[35], the annual runoff of the Yellow River in its upper and middle catchments had displayed an increase trend since the 1920s[36], and the Hongjiannao Lake in the boundary between Shaanxi Province and Inner Mongolia was formed in the 1920s and enlarged thereafter[25]. These indicate that precipitations in the middle and western parts of north China were indeed increased in the 20th century. After processing all the proxy data of precipitations (including accumulation rates in the Guliya and Dunde ice cores, tree-ring data in Delingha) and dust events (recorded in the Chongce, Malan and Dunde ice cores) in the northern Tibetan Plateau by the normalization method, we could easily synthesize one normalized precipitation time-series data set (Figure 7(b)) and one normalized dust-event time-series data set (Figure 7(a)). By comparing these two normalized data sets, it was found that there was a strong negative correlation between them (Figure 8), and the correlation coefficient was $-0.745$ at significance level of 0.1%. All these indicate that the increase in precipitations over

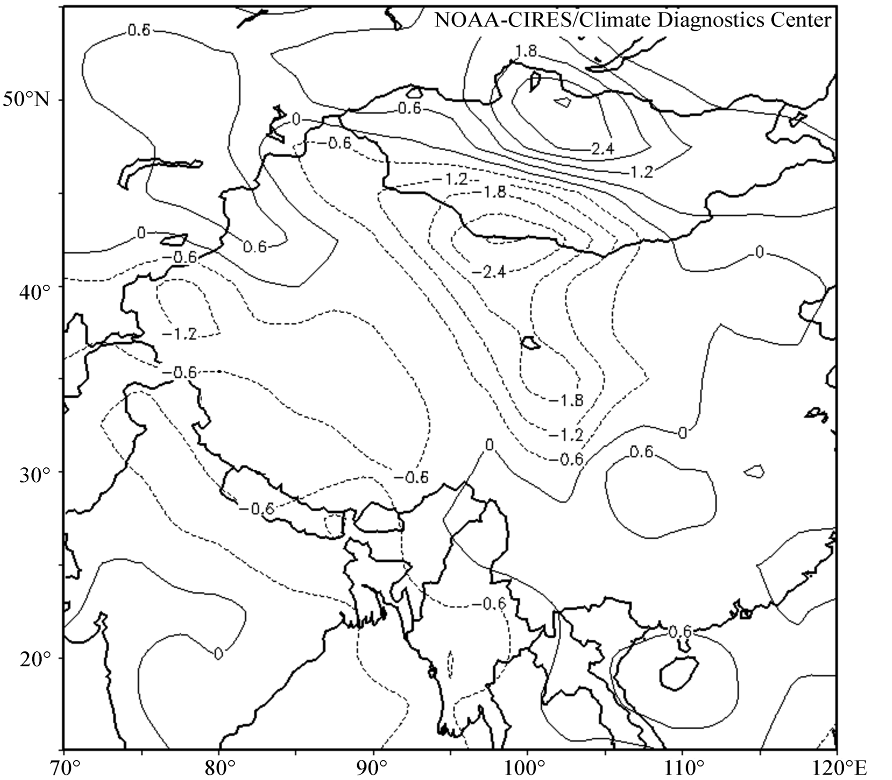


**Figure 5** Differences between mean zonal surface wind speeds in spring (March through May) during the periods of 1980—1999 A.D. and 1960—1979 A.D. (data available at http://www.cdc.noaa.gov). The contour interval is 0.6 m/s.

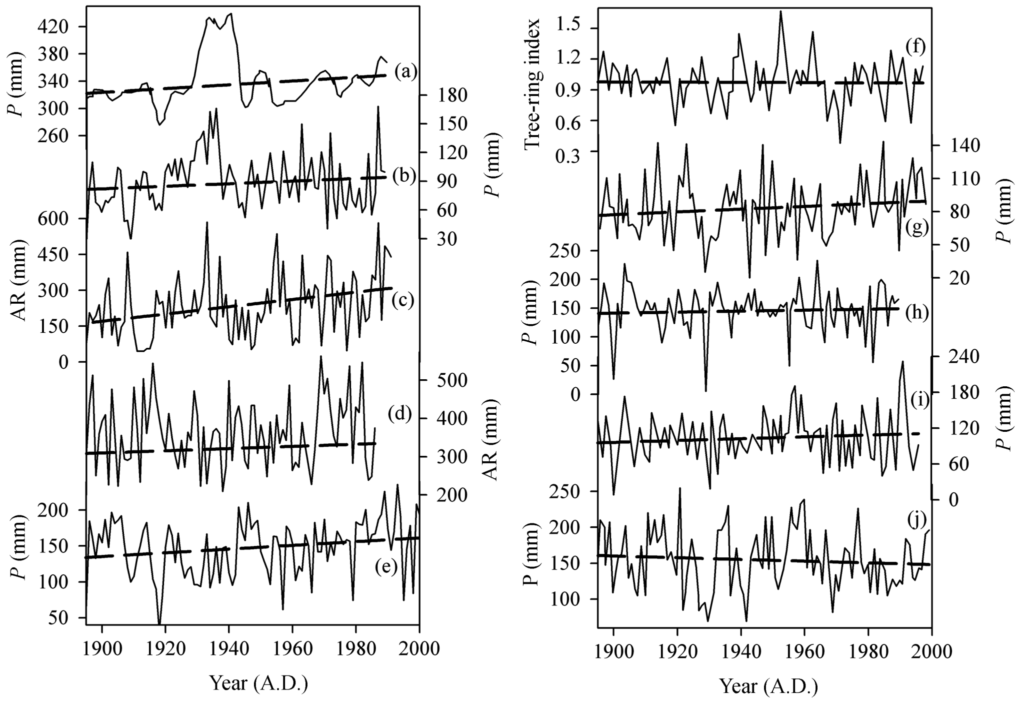


**Figure 6** Variations in precipitations over last 100 years revealed by tree-ring and ice core records in north China. (a) Precipitation from previous June through next May in the west Tianshan Mts.[12]; (b) precipitation during June through September in the east Tianshan Mts.[13]; (c) accumulation rate (AR) in the Guliya ice core from the West Kunlun Mts.[14]; (d) accumulation rate in the Dunde ice core from the Qilian Mts.[22]; (e) precipitation from previous July through next June in Delingha, Qinghai[15]; (f) tree-ring index in the east Qilian Mts. (reflecting precipitation during March through April)[16]; (g) precipitation during May through July in the Helan Mts.[17]; (h) precipitation during April through June in Huangling, Shaanxi[18]; (i) precipitation during February through June in the Daqingshan Mts.[19]; (j) precipitation during April through early July in the Da Hinggan Mts.[20]. In the ordinates, *P* represents for precipitation, and AR for accumulation rate.

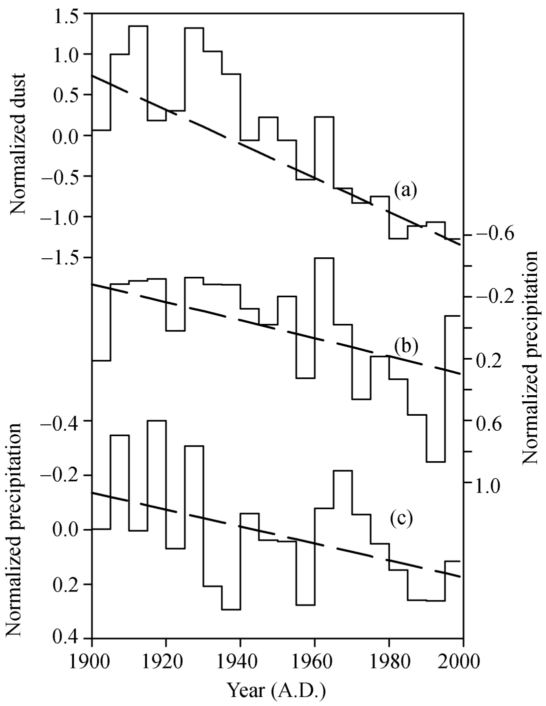


**Figure 7** Variations of the normalized time-series data sets of precipitations and dust events over the last 100 years. (a) Dust events recorded in the northern Tibetan ice cores; (b) precipitation in the northern Tibetan Plateau; (c) precipitation in north China. Note the values of precipitation ordinates increase downwards.

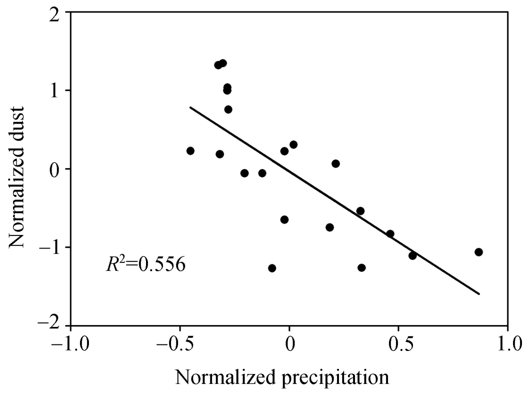


**Figure 8** Correlation between precipitation and dust concentration in the northern Tibetan ice cores.

the last 100 years in most parts of north China (see Figures 6 and 7(c)) is also an important reason for the decrease in dust event frequency in north China.

Traditionally, it is presumed that dust event frequency is positively related with the areal extent of desertification[37]. However, it is worth noticing that dust event frequency displayed a decrease trend in north China over the past 50 years, which is mentioned above, while the areal extent of desertification in north China expanded acceleratedly, for example, the expanding rate of desertification was 1560 $km^2$/a during the period from the 1950s to the middle of the 1970s, 2100 $km^2$/a during the period from 1976 to 1988 A.D., and up to 3600 $km^2$/a during the period from 1988 to 2000 A.D.[38]. These phenomena are contradictory, or the major causes of dust events are different from that of desertification in recent years? Most observations and experiments[34,39−43] showed that modern desertification was related with human activities. With populations growing, excessive cultivation, overgrazing, removal of shrubs and trees for fuelwood, and abuse of water resources ravaged the natural vegetation and surface soil texture in the semi-arid and arid zones in north China, where the original ecosystem and environment are frangible and vulnerable. These could lead an increase in soil erosion by wind, and make the extension of desertification at a rate larger than its natural rate by a factor of several to hundreds [39]. Moreover, geological sediment records[44−46] indicated that the east boundary of deserts/sands in north China at present extend eastward 10° longitudes farther than that during the Holocene Optimum, and is close to that during the last glacial maximum. It should be emphasized that the climatic condition at present in north China is similar to that during the Holocene Optimum to some extent. This suggests that the areas with sands in the eastern part of north China should be grassland at present, which implies that modern desertification in north China might likely be the consequence of human activities. Therefore, over the last several decades, the extension of desertification in north China was mostly caused by human activities, while the decrease in dust event frequency in north China was mostly controlled by climatic factors. But we should be aware that the increase in desertification in north China by human activities might enhance risk for dust occurring on large spatial scale and with high strength under the future climate change.

## 4 Conclusions

The role of dust in climate system was recognized just two or three decades ago. Otherwise, dust can exert a severe influence on human health[47]. Thus much attention has been paid to the study on the variations in frequency of dust events, especially those occurring in dust source areas and their vicinities. North China is an important part of dust source areas of central Asia. In this paper, we analyzed the variations of dust events recorded in the Dunde, Malan and Chongce ice cores from the mountains in the margin of arid regions of northwest China and that recorded in the Hongjiannao lacustrine sediment core from north Shaanxi Province, and found that the dust events occurred frequently and strongly in the first half of the 20th century, especially in the late 1920s and 1930s, and the trend of dust event frequency went down over the last 100 years. By comparing dust events with climatic conditions, it is recognized that the decrease trend in dust event frequency over the 20th century might be caused mostly by the natural processes, including increasing precipitation and weakening westerly which might be related with global warming. Moreover, we found that precipitations over the last 100 years showed an increase trend in the middle and western parts of north China, but a decrease trend in the eastern part of north China. This spatial pattern of the variations in precipitations in north China was also shown by the meteorological observation data over the last several decades[48].

Human activities have intervened excessively in the fragile ecosystem and environment in the semiarid and arid regions in north China, and have made the order of nature, i.e. the concurrence of desertification and its concomitant frequent and calamitous dust events, be broken. And thereby, much attention should be paid to the possibility and impacts of dust events occurring on large spatial scale, which might appear under the future climate change owing to the extension of dust source area by desertification. In order to mitigate and prevent dust events, the works of the ecosystem construction and environmental conservation should be done and reinforced in north China as soon as possible.

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