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# Variability of East Asia dust events and their long-term trend

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**Abstract**

In order to examine the decadal variations of the dust events over East Asia, we analyze surface observations from 701 meteorological stations for the period 1960–2004 to obtain spatial and temporal distributions of dust events. Since the Taklamakan Desert in western China and the Gobi Desert in Inner Mongolia are the two major sources of dust storms, we have defined two dust indices, one for the Taklamakan Desert Index (TDI) and one for the Gobi Desert Index (GDI), to characterize the statistical nature of the dust events over these two regions. Both of these indices are well correlated with the Total Ozone Mapping Spectrometer (TOMS) Absorbing Aerosol Index (AAI). TDI and GDI time series exhibit a decreasing trend since the mid-1980s, and is likely caused by an enhanced geopotential height over the Mongolian plateau and the middle Siberian region, as well as by an anomalous shift in the phase and intensity of the stationary wave over.


*Keywords:* East Asia; Taklamakan Dust Index (TDI); Gobi Dust index (GDI)

## 1. Introduction

Dust aerosol in the atmosphere has a significant direct and indirect effect on climate on various spatial scales, from local and regional to global (Huang et al., 2006a). Jaffe et al. (2003) have shown that extreme episodes of dust transport can adversely impact air quality in regions far from the original emission source. China, as a primary source of dust in Eastern Asia, has drawn much scientific attention. Dust from East Asia desert regions can sweep across the entire North China (Zhang et al., 2003) and a large portion of East China, before being finally deposited into the Pacific (Duce, 1983; Shaw, 1980); it can on occasion reach North America (Husar et al., 1997, 2001; Jaffe et al., 1999; Uematsu et al., 1983; Uno et al., 2001).

The Taklamakan and Inner Mongolian Gobi Deserts are the two main dust event centers in China. Each year there are more than 10 dust storms, resulting in more than 20 dust events observed at some observational stations (Zhou, 2001). In all, it has been estimated that about 800 Tg of dust is injected into the atmosphere annually, which may be as much as half of the global production of dust (Zhang et al., 1997). Sun et al. (2001) and Qian et al. (2002) both showed that the Taklamakan and Gobi Deserts in Northern China and Southern Mongolia, respectively, are the main sources of dust storms in East Asia. Hsu et al.

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(2006) also used radiance measurements from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) data to investigate the primary dust aerosols in Northern China, as well as over the Taklamakan Desert and the Gobi Desert in Inner Mongolia. In this study, these two regions are chosen as two centers of dust to investigate dust events over China.

A number of previous researches have studied dust events in China using meteorological data from Chinese weather stations (e.g., Zhang et al., 2001; Qian et al., 2002; Xuan and Sokolik, 2002). For instance, Sun et al. (2001) analyzed wind speed, precipitation and dust storms from 174 Chinese weather stations from 1960 to 1999. Using station-averaged annual time series of dust storm days from 83 stations in Northern China, Qian et al. (2002) showed a decreasing trend of dust storms from 1954 to1998. Dust weather types have also been developed and analyzed from 1954 to 1998 using data from 338 Chinese stations (Wang et al., 2003; Zhou and Zhang, 2003). Recent studies have used satellite observations to describe the large-scale dust-loading of the atmosphere over China (Darmenova et al., 2005; Washington et al., 2003), over the oceans (Husar et al., 1997), and globally (Herman et al., 1997). The objective of our study is to employ a dust index, one for the Taklamakan Desert Index (TDI) and another one for the Gobi Desert Index (GDI), that can provide a summary of the statistical character of the dust events over these two regions, as well as providing a convenient way of establishing a causal relationship with the atmospheric circulation.

The paper is organized as follows. A description of data sets used is given in Section 2. Section 3 defines the two dust indices, TDI and GDI, and Section 4 makes a comprehensive comparison of TDI (GDI) with satellite remote sensing data (TOMS AI). Using TDI and GDI, Section 5 gives an analysis of the long-term trend of the two indices. Conclusions are given in Section 6.

## 2. Data

Monthly meteorological data associated with dust events from 701 meteorological stations for the period 1954–2000 are provided by the National Meteorological Center of the China Meteorological Administration (Wang et al., 2003; Ding et al., 2005). The total number of days of dust event occurrences for spring (March–May) from 1960 to 2004 used in this study are provided by the Gansu Meteorological Information Centre. Of the stations used, four stations in Taklamakan and four stations in Inner Mongolia are chosen to establish two new dust indices. The monthly mean 500 hPa height field data employed in this study are from the National Centers for Environmental Prediction/National Center for Atmospheric research (NCEP/NCAR), on a $2.5 \times 2.5$ degree grid for the period 1960–2003. The Absorbing Aerosol Index (AAI) used in this paper is an index indicating the presence of ultraviolet (UV)-absorbing aerosols in the Earth's atmosphere, and is derived from a residual of the measured reflectance in the UV (Herman et al., 1997; Torres et al., 1998; De Graaf et al., 2005). The AAI has been used for a long time in remote sensing to indicate UV-absorbing aerosols, like desert dust (e.g., Chiapello et al., 1999; Alpert and Ganor, 2001; Pandithurai et al., 2001; Spichtinger et al., 2001; Prospero et al., 2002; Moulin and Chiapello, 2004). Initially developed as an error estimate in the Total Ozone Mapping Spectrometer (TOMS) ozone retrieval algorithm (Herman et al., 1997; Torres et al., 1998), the residual and the AAI records have become the longest records of global aerosol measurements available. Starting in 1978, the American TOMS instruments have provided daily global aerosol maps, with a data gap only between May 1993 and June 1996. The monthly mean AAI data are used in this study and the spatial resolution of the data is $1^\circ$ (latitude) by $1.25^\circ$ (longitude). The TOMS AAI data contain only the aerosol index values greater than or equal to 0.7, since values below it could be contaminated by noise resulting from surface signal or non-absorbing aerosols (Herman et al., 1997).

## 3. Spatial distribution characteristics of dust events

Based on the available original dust event records from the 701 meteorological stations, we discuss the distribution of 47-year (1954–2000) mean of the number of days of occurrence of spring dust events in Northern China. Dust events can be classified into three categories, depending on the meteorological condition: floating dust (FD), blowing dust (BD) and dust storm (DS). Table 1 shows the meteorological conditions for those three kinds of dust events. In the FD category, dust aerosols are suspended in the air under calm or low-wind condition, with horizontal visibility usually below

Table 1
The definition of three type dust events

| Type | Wind | Visibility | Atmospheric condition |
|---|---|---|---|
| FD (floting dust) | Low | 1–10 km | Suspended |
| BD (blowing dust) | Strong | 1–10 km | Turbid |
| DS (dust storm) | Strong | <1 km | Turbid |

10 km. In the BD category, dust and sand aerosols are physically lifted off the ground by winds, causing horizontal visibility to go significantly below 10 km. In the DS, sand and fine dust aerosols are frictionally lifted from the ground by strong winds (usually in excess of $5\,m\,s^{-1}$) under turbid atmospheric condition (Gillette, 1978). The horizontal visibility is reduced to below 1 km. Fig. 1 shows the spatial distribution of 47-year mean of the number of days of occurrence during springtime of dust storms (Fig. 1a), BD (Fig. 1b) and FD (Fig. 1c) in China. Dust events occur mainly in the arid and semiarid areas during the period from March to May (Littmann, 1991; Zhou and Wang, 2002).

It can be seen from Fig. 1a that there are two major source regions of sand–dust storms: the Gobi Desert in Inner Mongolia along the Northern China, and the surrounding areas of the Taklamakan Desert in Xinjiang. Dust aerosols from the Taklamakan Desert can be entrained to an elevation of >5000 m and then transported over long distances (~5000 km) by the prevailing winds (Sun et al., 2001). BD and FD not only occur mainly in the areas where DS occurs, but also extend to the surrounding areas. Fig. 1b shows that the range of BD is larger than DS, extending to the northeastward and southeastward areas. The BD condition can occur more than 30 days in the Taklamakan and Gobi regions. Fig. 1c shows that the frequency of occurrence of FD is the highest among the dust events. The range can reach in most part of Northern China and can extend southeastward to the low-latitude region such as the East China Plain and the areas of the middle and lower reaches of the Changjiang River. FD occurs more frequently than BD and DS in the high-latitude areas such as Taklamakan Desert region. It is obviously seen by comparing with DS and BD, there are above 80 days of the 47-year mean annual occurrence days of FD in the Taklamakan Desert region. There are above 50 days of BD which occur every year in the Inner Mongolian Gobi region. As expected, the mean FD values for the Inner

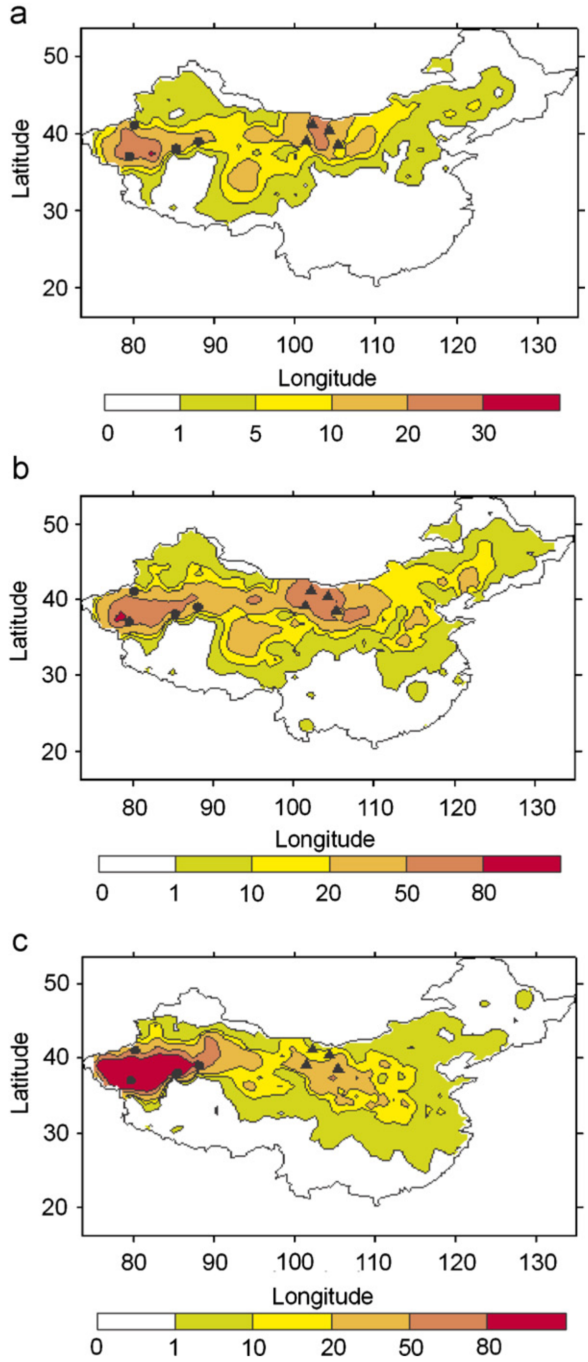


Fig. 1. Distribution of 47-year (1954–2000) averaged surface observed occurrence days of spring DS, BD and FD in northern China. The four selective stations in Xinjiang and Inner Mongolian regions are marked by dots and stars, respectively.

Mongolian region (Fig. 1c) are considerably smaller than BD and DS from this region. A frequency distribution of the each dust event category is shown in Fig. 2. It is interesting to note that the frequency of FD in the Taklamakan area (44.4) is significantly greater than is observed in the Gobi Desert (5.3), while similar frequency values are indicated in these two regions for BD and DS dust events. The difference in the character of the dust events between these two regions is related to the presence of significantly more vegetation coverage at Gobi than at Taklamakan. At Gobi, the wind speed must exceed a certain magnitude before it can lift dust and sand upward, but at Taklamakan where there is little or no vegetation, dust sources are abundant and even a weak wind can lift sand off the ground. This results in a significantly more number of FD days at Taklamakan than at Gobi. In addition to the difference in the vegetation cover between these two regions, difference in the topography is another important factor. Since Tarim is a closed basin, mobilized dust often floats in Taklamakan, and rarely escapes the surrounding mountain ranges unless the wind is strong enough. Difference in the soil types is also another important contributing factor, as Taklamakan soils are composed mainly of fine sands, while Gobi soils contain coarse sand/pebbles/cobbles, which require stronger winds to initiate dust emission. These results are consistent with the results presented by Wang et al. (2003), although they have used a different method which is called clustered analysis.

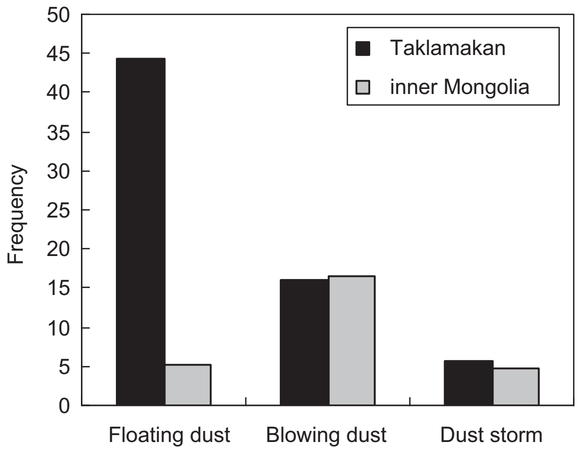


Fig. 2. The frequency of floating dust, blowing dust and dust storm for Taklamakan and Inner Mongolia.

## 4. Definition of dust indices

Ding et al. (2005) defined a DS frequency index (DSFI) by averaging the total occurrence days of dust storms for springtime (March–May) from 48 stations. The monthly averaged occurrence days of dust storms, BD and FD were used in index calculations to study the spatial distribution characteristics of dust events (Wang et al., 2003). In order to develop a new Taklamakan Desert Index (TDI) and a Gobi Desert Index (GDI), which can characterize the regional statistical and large scale nature of the dust events in these two regions, four representative stations from each desert region are selected (see Fig. 1 and Table 2) through correlation analyses of meteorological stations in these two desert regions. The correlations in the frequency of monthly DS days among the four selected stations in Inner Mongolia are above 0.3, while those in the Taklamakan region are greater than 0.6, both correlation values being statistically significant at the 99% level. This statistical analysis indicates that the combination of the four stations used in this study is effective in representing the large scale nature of the dust events. Huang et al. (2006b) also used TDI to study the long-term statistical relationship between DS and cloud properties.

In order to obtain a relationship among the DS, BD and FD categories of dust events, Niu et al. (2001) examined the relative concentration differences among these categories by analyzing 15 dust

Table 2
List of sites of the Xinjiang and Inner Mongolia regions with their name latitude, longitude, altitude, date of dust events used

| Area | Name | Latitude | Longitude | Altitude | Date |
|---|---|---|---|---|---|
| Xinjiang | Hetian | 37.08 | 79.56 | 1374.6 | 1 January 1954–31 December 2004 |
| Xinjiang | Qiemo | 38.09 | 85.33 | 1247.5 | 1 January 1954–31 December 2004 |
| Xinjiang | Akesu | 41.10 | 80.14 | 1103.8 | 1 January 1954–31 December 2004 |
| Xinjiang | Ruoqiang | 39.02 | 88.10 | 888.3 | 1 January 1954–31 December 2004 |
| Neimenggu | Alasyq | 39.13 | 101.41 | 1510.1 | 1 January 1960–31 December 2004 |
| Neimenggu | Alaszq | 38.50 | 105.40 | 1561.4 | 1 January 1960–31 December 2004 |
| Neimenggu | Guizihu | 41.22 | 102.22 | 960 | 1 January 1960–31 December 2004 |
| Neimenggu | Bymd | 40.45 | 104.30 | 1328.1 | 1 January 1960–31 December 2004 |

event cases from 1995 to 1998 in the Mu Us and Badain Jiran desert regions of Inner Mongolia. They found that, if a DS occurs at a station, its concentration is almost 3 times greater than the value of BD, or 9 times greater than the value of FD. Based on this finding, we define the following composite dust index for TDI and GDI:

$$T(G)DI = FD + BD*3 + DS*9,$$

where FD, BD and DS have units of concentration of dust. Here, FD is a relative normalized quantity and is assigned a value of 1. The TDI values are obtained from FD, BD and DS values determined from the four stations in Taklamakan. Similarly, the GDI values are obtained from using the four stations in Gobi. The monthly means of TDI (a) and GDI (b) are plotted in Fig 3. The overall 45-year (1960–2004) mean TDI value of 136.2 is about 41% greater than the mean GDI value of 96.4.

The AAI archive by TOMS constitutes an easy-to-use satellite data set available for the entire globe. In order to identify the major dust production areas during our period of study, we used the TOMS AAI data to confirm the spatial representativeness of TDI and GDI. The TOMS AAI data confirm the Taklamakan/Tarim region as a major source (Washington et al., 2003), although there are still some areas which TOMS does not identify as being major source regions such as the Inner Mongolian Gobi Desert.

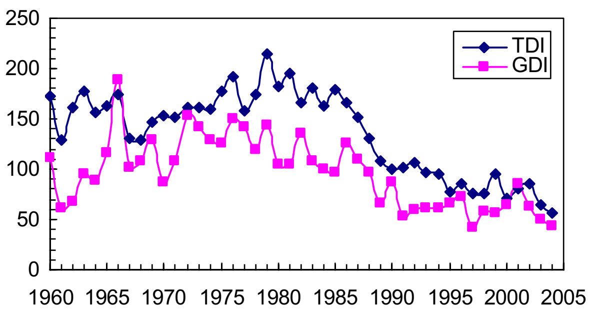


Fig. 3. Times series of TDI and GDI for the period of 1960–2004.

To investigate the relationship between the variability of dust events and the AAI data, we carry out a simple linear correlational analysis between the indices and the AAI data after eliminating their decadal trends. Fig. 4 shows the spatial distribution of the correlational relationship between AAI and (a) TDI and (b) GDI. The distribution shows the spatial extent of dust events that originate in each of the major sources, as well as the ability of remote sensing of dust aerosols by TOMS. In Fig. 5a, it is no surprise to see a center of statistically significant correlation of greater than 0.5 over the Taklamakan Desert region; however, it is interesting to note another small center of high correlation over the Gobi Desert area. This implies that the meteorological condition that gives rise to a dust event at Taklamakan also gives rise to a dust event at Gobi. In Fig. 4b, we see that over the Gobi Desert region GDI shows a correlation of about 0.5 with AAI. There is a large region of statistically significant correlation stretching eastward from the Gobi source region, indicating the role of atmospheric circulation and advection in transporting dust aerosols for long distances from the source regions.

## 5. Variability and long-term trend

Long-term trends of the Spring TDI and GDI are given in Fig. 5. It can be seen that both TDI and

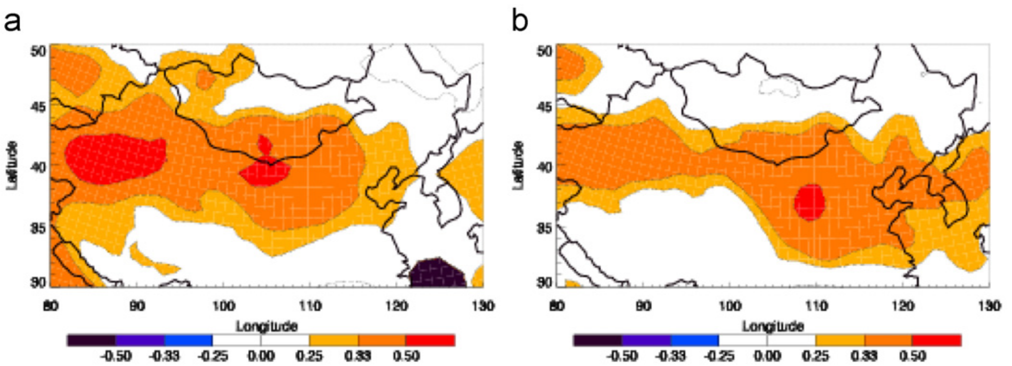


Fig. 4. Spatial correlation between monthly anomalies of: (a) TDI, (b) GDI and TOMS AI (detrend). The correlation coefficients are 0.25 and 0.33 at the 95% level and 99% level.

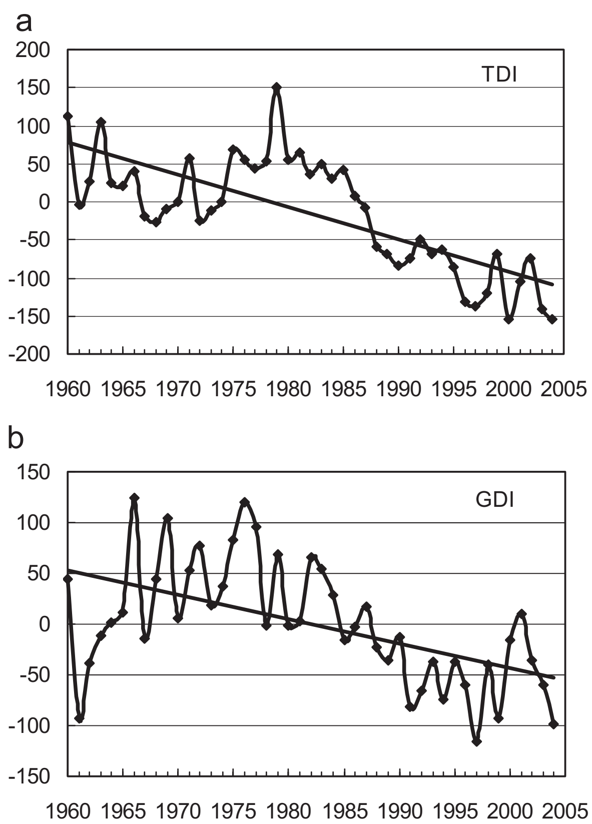


Fig. 5. Variations of annual mean: (a) TDI and (b) GDI from 1960 to 2004 during springtime.

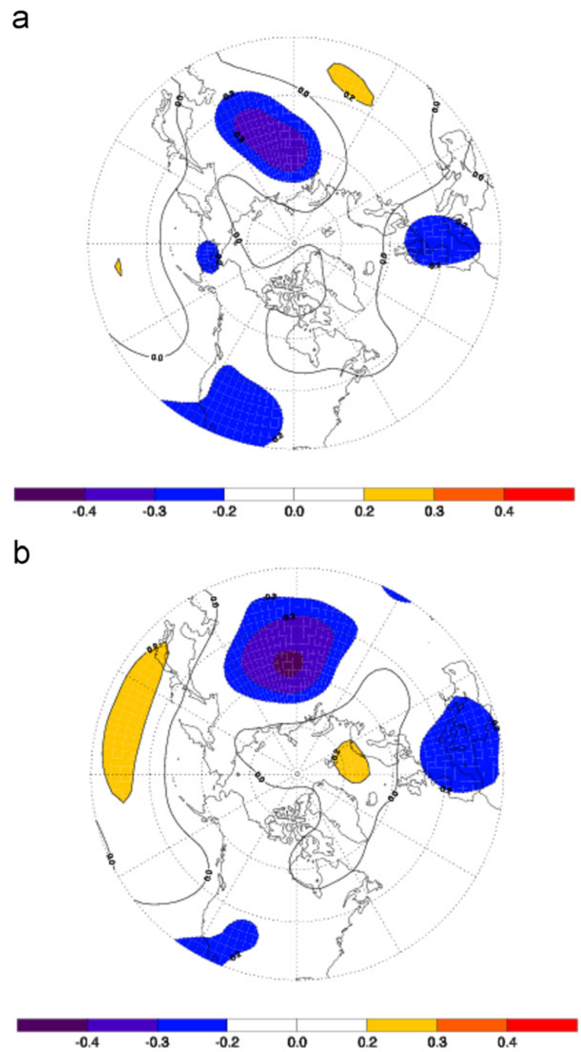


Fig. 6. Correlations between (a) the spring TDI, (b) the spring GDI and 500 hPa geopotential height for the period 1960–2003. The correlation coefficients are significant at the 95% level and 99% level are shaded. The latitude lines are at 15° intervals starting with 30°N at the outer edge.

GDI show a decreasing trend. This long-term trend is influenced to a varying degree by the three kinds of dust events. We will show that the decrease in the indices is associated with a change in the circulation pattern over the Asian continent. Toward this end, we first perform a correlational analysis between the indices and the 500 hPa geopotential height field to obtain teleconnection patterns for the spring season March–May, when most of the dust events are observed. Correlation coefficient at each grid is based on a sample size of $44 \times 3 = 132$ values (44 years and 3 months per year). Fig. 6a shows a correlation map between the TDI and 500 hPa geopotential height. It indicates an area in the Northwest China with significant negative correlation of $-0.4$ centered over the Xinjiang region, with correlation values being statistically significant at the 99% level of significance are shaded. This suggests that the above normal occurrences of springtime dust events are closely associated with negative 500 hPa height anomalies and that the below normal occurrences are closely associated with positive 500 hPa height anomalies in these regions. Fig. 6b gives a similar correlation map for GDI. The map shows a center over the Mongolian plateau with a statistically significant correlation value of $-0.35$. In both correlation maps, dust events at Taklamakan and Gobi appear to be associated with the circulation anomalies.

In order to differentiate the atmospheric circulation pattern associated with dust events from that associated with non-dust events, we derive two Northern Hemisphere 10-year composite 500 hPa

Table 3
Composite years (TDI)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| High-frequency years | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1985 |
| Low-frequency years | 1990 | 1991 | 1995 | 1996 | 1997 | 1998 | 2000 | 2001 | 2002 | 2003 |

geopotential-height anomaly maps, one associated with high-frequency and another with low frequency spring occurrences of dust events in the Taklamakan and Gobi Desert regions. (See Table 3 for the years chosen for the composite analysis.) High-frequency years are associated with large positive anomaly TDI values, and low-frequency years with large negative anomaly values. For the high-frequency years of DS occurrence in Taklamakan area, the dominant geopotential-height anomaly field is shown in Fig. 7b. It shows that there is an anomalous weak polar vortex and a strong East Asian major trough. For the low-frequency years shown in Fig. 8b, there is a strengthened polar vortex and a weak East Asian major trough. These changes cause conditions over Northwest China to shift from the ahead-of-ridge and back-of-trough region in the high-frequency years to the ridge region of the stationary wave during the low-frequency years, leading directly to the weakening of northwest air flow over Northwest China (Ding et al., 2005). Fig. 9 shows the difference field constructed by subtracting Fig. 7b from Fig. 8b. In Fig. 9, it can be seen that there is an enhanced geopotential height in 45°–60° latitude belt over the north and center parts of the Siberian high with a strong anomalous anticyclone, causes anomalous northerly winds to occur over the eastern part of China and anomalous southerly winds over the western part of China, which tend to weaken the intensity of northwest cold air flow from higher latitudes to Northwest China. This process appears to be responsible for the springtime decreasing of the frequency of strong winds in Northwest China, which is the most important change in atmospheric circulation contributing to the decreased frequency of dust events in Northwest China (Zhou et al., 2001; Ding et al., 2005). Qian et al. (2002) showed that the frequencies of dust storms and dust weather in the 1950s–1970s were about twice that after the mid-1980s in the eastern part of China, the reason for this feature may be due to the warming in Mongolia and cooling in northern China that reduced the meridional temperature gradient, resulting in the reduced cyclone frequency in Northern China. In the Tarim Basin, the high-frequency dust storms have been attributed to less precipitation and to the arid-heating climate.

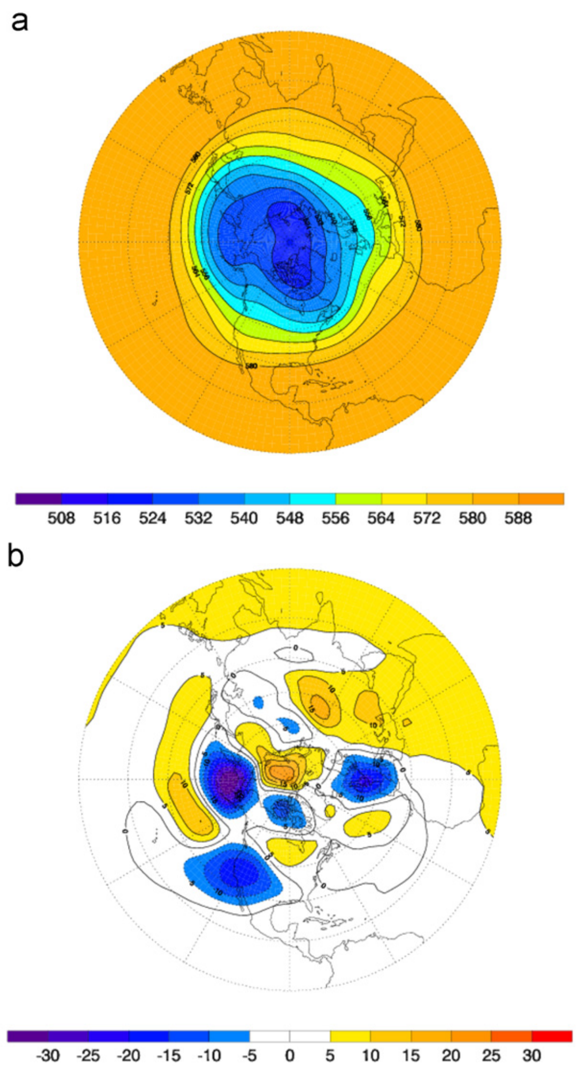


Fig. 7. (a) 500 hPa average field and (b) 500 hPa anomaly field in high-frequency years.

A similar analysis of 500 hPa geopotential-height anomaly associated with springtime DS occurrences has also been carried out for the Gobi Desert region, and the result (not shown) is similar to the one shown in Fig. 7.

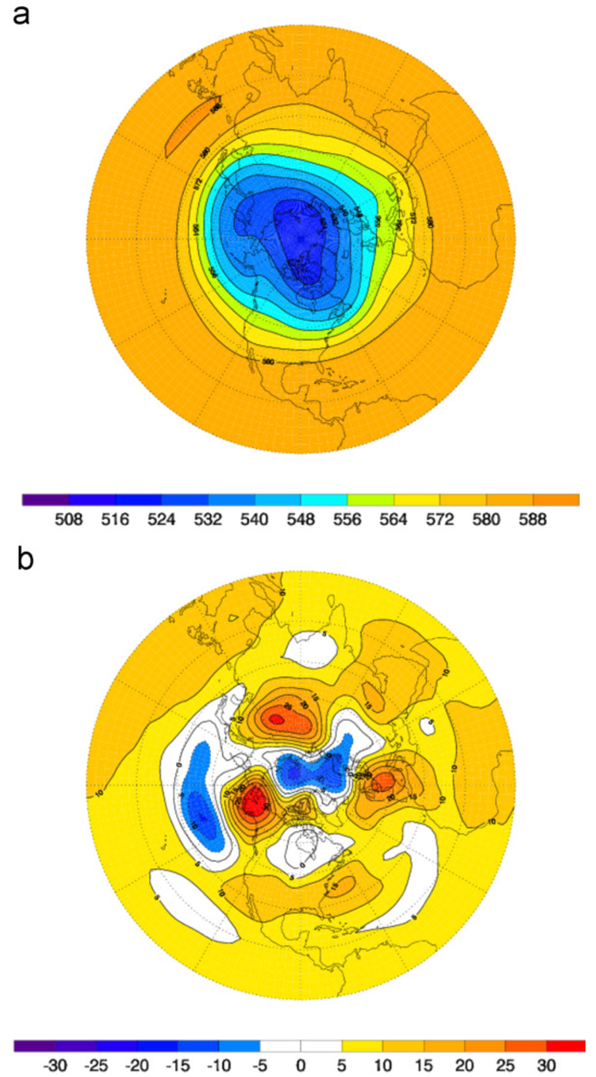


Fig. 8. (a) 500 hPa average field and (b) 500 hPa anomaly field in low-frequency years.

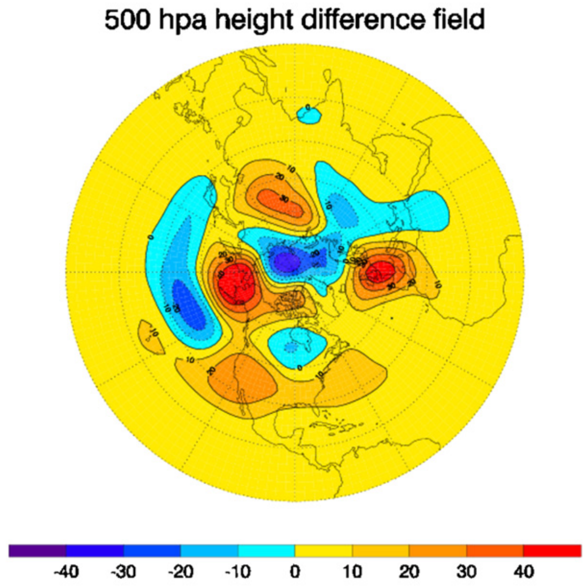


Fig. 9. The composite differences in spring 500 hPa geopotential height between the low- and high-frequency years.

## 6. Conclusions and discussion

In this study, we have analyzed surface observations from 701 meteorological stations for the period 1954–2000 to obtain spatial and temporal distributions of dust events in Northern China. We have also derived two dust indices, one for the Taklamakan Desert region (TDI) and another one for the Gobi Desert region (GDI). The dust index allows us to characterize the statistical nature of the dust events over a climatological period for each of these major source regions in East Asia. Based on visibility and wind speed, dust events have been categorized into three types (Table 1): floating dust (FD), blowing dust (BD), and dust storm (DS). We have found that the mean annual maximum number of occurrences of the DS type is about 40 for the Taklamakan region and about 20 for the Gobi region.

We have also used TOMS AAI data to confirm the spatial representativeness of TDI and GDI. Although TOMS fails to identify some major source regions of dust aerosols, such as the Inner Mongolia region, there is an overall statistically significant spatial correlational relationship between the two dust indices and the TOMS AAI data. This gives confidence in the ability of the dust indices to reflect the large spatial extent of dust events.

We have also found that both TDI and GDI show a significant linear decreasing trend during the 1960–2004 period. The decrease is most noticeable from around 1980 to the mid-1990s. The decreasing trend in the indices is associated with a change in the tropospheric circulation pattern over the Asian continent. Spatial correlational analysis (teleconnection) between the dust indices and the 500 hPa geopotential height anomaly fields shows that the above (below) normal occurrences of springtime dust events are associated with negative (positive) 500 hPa height anomalies. The development of a strong anomalous anticyclone over Siberia has weakened the intensity of the northwesterly winds over Northwest China during the springtime. This process is the most important change in the atmospheric circulation contributing to the decreased frequency of dust events in Northwest China.

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