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Key Points:
- Temporally, the clustering of severe dust storm activity in a year has intensified after 1985 in China
- Spatially, severe dust storms were once documented across China in the 1950s but primarily in north and northwest China after the 2000s
- The relative frequency of severe dust storms with a large impact area has increased in north and northwest China

Supporting Information:
- Supporting Information S1

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The Clustering of Severe Dust Storm Occurrence in China From 1958 to 2007

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Abstract China is subjected to severe dust storms that deteriorate air quality and cause substantial damages to environment and socioeconomics. Although the annual frequency of severe dust storms in China has been declining since the 1950s, the variability of severe dust storm occurrence in time and space remains inadequately described under the changing climate. Based on the continuous observation at 368 meteorological observation sites across the mainland China over a 50-year period (1958 to 2007), we found that the temporal clustering of severe dust storm outbreak has intensified after 1985, which exacerbated the irregularity in the monthly distribution of severe dust storms. Moreover, the timing of the clustering has shown a higher interannual variation after 1985. Therefore, the variability of severe dust storm occurrence has increased significantly since the 1980s at the annual and monthly time scales. In addition, the relative probability of experiencing severe dust storms with a large influential range has risen since the 1980s. Spatially, severe dust storm outbreak has receded from spreading across the country in the 1950s to primarily affecting north and northwest China in the 2000s. These findings suggest a relatively higher risk of dust storm disaster in north and northwest China that is associated with the intensified clustering of severe dust storm activity in both time and space. Continuous studies are needed to identify the favorable synoptic system that stimulates the clustering of severe dust storm outbreak. We advocate more efforts to enhance severe dust storm prediction and warning dissemination in north and northwest China.

1. Introduction

Linking large-scale climate trends to the localized pattern of severe weather has become an important issue of significant public and scientific interest (Brooks et al., 2014; Easterling et al., 2000; Zheng et al., 2015). For example, a recent study indicated that along with the weakening of East Asian summer monsoon, the number of severe weather days in China has undergone a significant decrease over the past five decades (Zhang et al., 2017). In addition to the long-term trend in occurrence frequency, a comprehensive understanding of severe weather climatology asks for examining the variability of severe weather occurrence (Brooks et al., 2014), such as the change in outbreak time and area. This knowledge is of practical significance for severe weather prediction, warning dissemination, and disaster mitigation (Feng et al., 2017; Meehl et al., 2000).

However, the variability of severe weather climatology under the warming climate has not been adequately characterized (Brooks et al., 2014; Easterling et al., 2000). The difficulty is in part due to the lack of continuous observations with a reliable and coherent spatiotemporal coverage (Brooks et al., 2014; Zhang et al., 2017). Moreover, effective quantification of severe weather variability in time and space remains challenging (Brooks et al., 2014). Therefore, continued efforts are needed to enhance the observation, quantification, and prediction of the variability of severe weather climatology.

In China, severe dust storms are recognized as a major type of the disastrous weather that intensely impacts air quality and causes substantial damages to environment and socioeconomics (e.g., Li et al., 2009; Qian et al., 2002; Wang et al., 2004). The vast arid and semiarid region in north and northwest China (~3.57×10^{-6} km^2) is one of the primary dust source regions around the world (Shao & Dong, 2006), making China subjected to annual severe dust storm threats, especially in spring (Zhou & Zhang, 2003). The Chinese government has launched a series of large-scale projects to combat desertification and mitigate dust storm disasters, such as the "Three-North" Shelter Forest Program, the "Grain for Green" Program, and the Beijing–Tianjin Sand

Source Control Program that started in 1978, 1999, and 2001, respectively (Middleton, 2016; Tan & Li, 2015). In the meantime, many studies have been carried out to monitor and predict the long-term trend of severe dust storm frequency. These studies indicated that the annual frequency of severe dust storms in China has been declining since the 1950s, which is likely associated with the changes in atmospheric circulation and rainfall patterns, the weakening of the westerly jet stream, and a greater vegetation coverage (e.g., Ding et al., 2005; Fan et al., 2014; Liu et al., 2004; Middleton, 2016; Wang et al., 2017; Zou & Zhai, 2004). Such a downward trend in severe dust storm activity in China is concurrent with the warming climate and is predicted to be sustained in the future (Fan et al., 2014; Goudie, 2009; He et al., 2015; Zhu et al., 2008). However, whether or not the variability of severe dust storm occurrence has altered under the changing climate remains elusive (Shao & Dong, 2006). We hypothesize that, aside from the decreasing trend in the annual frequency, the variability of severe dust storm climatology, for example, the temporal and spatial distribution of severe dust storm outbreak, has also changed in China over the past several decades.

To test this hypothesis, we examined the 50-year (1958–2007) record of severe dust storms from 368 meteorological observation sites across the mainland China. Apart from the long-term trend, different quantitative indicators were developed to determine the variability of severe dust storms. Results of this study not only help understand severe dust storm climatology under the changing climate but are also of practical significance in alleviating dust storm damages in China.

2. Methods

2.1. Severe Dust Storm Records in China

Severe dust storm records used in this study were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). This official severe dust storm data set in China was produced by compiling the original daily records of dust storms and the related observations on gale and visibility based on the Surface Meteorological Monthly Bulletin and Wind-recorder's paper (Zhou & Zhang, 2003). Each record contained the detailed information on the start and end times of a severe dust storm, as well as observations on surface wind speed, wind direction, and visibility. According to the World Meteorological Organization protocol, this data set defined a dust storm with the visibility less than 200 m and the instantaneous wind speed over 20 m/s as a severe dust storm (Middleton, 1986). At each site, successive severe dust storm records with a time interval of less than 3 hr were merged into one record, representing the same severe dust storm process (Zhou & Zhang, 2003). In total, this data set archived severe dust storm records from 527 sites over the mainland China from 1954 to 2007. For further elaboration of this data set, readers are referred to the study by Zhou and Zhang (2003).

To ensure a relatively large and continuous data record, all of the 368 sites with complete severe dust storm records from 1958 to 2007 were retained for further analysis (Figure 1), including 46,668 severe dust storm records over a 50-year period. The other 159 sites with incomplete severe dust storm documents over the study period were excluded. The selected sites were categorized into three groups with different levels of severe dust storm frequency (Figure 2). We first summed severe dust storm records from 1958 to 2007 at each site and ranked the selected sites from 1 (with the least number of records) to 368 (with the most records). Then, the sites with ranks from 368 to 246, 245 to 124, and 123 to 1 were defined as the high-, medium-, and low-frequency severe dust storm sites, respectively (Figure 2). Throughout the study period, 89% of the total severe dust storm records were documented at the high-frequency severe dust storm sites, mainly located in the deserts and sandy lands (e.g., Gurbantonggut desert, Taklimakan desert, Qaidam Basin, and Gobi desert; Zhou & Zhang, 2003) or on the major paths of strong cold air outbreaks (e.g., Hexi Corridor; Zhou et al., 2011). However, less than 1% of the total records were documented at the low-frequency severe dust storm sites. The site groups showed a clear pattern of spatial aggregation, indicating a highly regionalized distribution of severe dust storms. As the distance from dust source regions increased, severe dust storm activity reduced from the northwest to the southeast of China (Figure 1).

2.2. The Long-Term Trend of Annual Severe Dust Storm Frequency

We examined the temporal dynamics of the annual frequency of severe dust storm across the selected sites from 1958 to 2007. Then, we calculated the linear trends over time of the annual severe dust storm records at the national scale and the number of meteorological observation sites with severe dust storms in each year. Furthermore, we compared the linear trend of the annual severe dust storm records at each of the high-

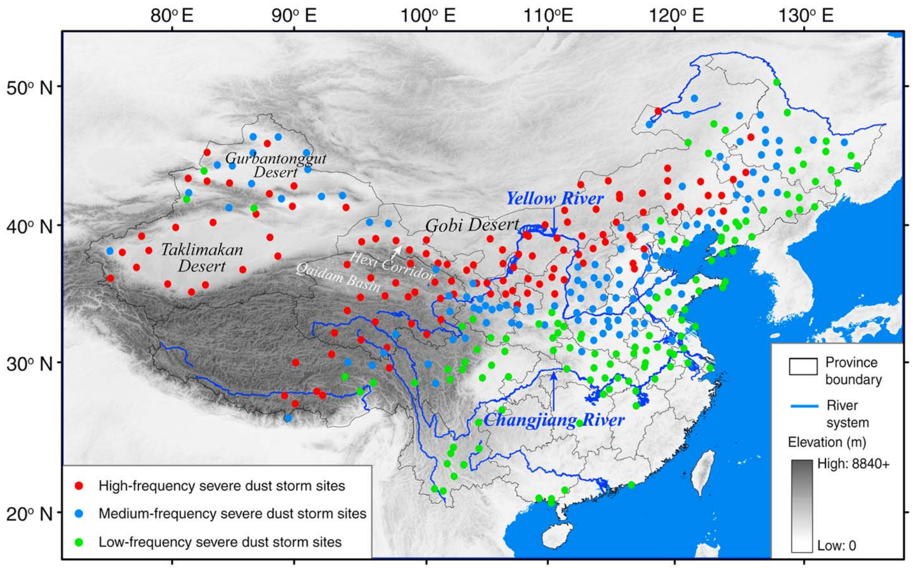

Figure 1. Spatial distribution of the 368 meteorological observation sites with continuous severe dust storm records from 1958 to 2007. Sites are categorized into three groups, including the high-frequency (the red dots), medium-frequency (the blue dots), and low-frequency severe dust storm sites (the green dots; see site classification in Figure 2). The base map depicts the topography of the study area using a 30-m resolution digital elevation model (DEM) from the global multiresolution terrain elevation data 2010 (GMTED2010), distributed by the USGS and the National Geospatial-Intelligence Agency (NGA) (http://earthexplorer.usgs.gov/).

frequency severe dust storm sites. The long-term trends at the medium- and low-frequency severe dust storm sites were likely biased by the relatively limited severe dust storm records (Figure 2) and thereby were not assessed.

2.3. The Temporal Variability of Severe Dust Storm Occurrence

At the national scale, we examined the sum of severe dust storm records in each of the calendar months from 1958 to 2007. The calendar months with the monthly maximum sum and monthly minimum sum in a year were identified, respectively. The occurrence time of the monthly extremes (i.e., monthly maximum sum and monthly minimum sum) in each year was compared over time to indicate the level of the temporal variability of severe dust storm outbreak. An irregular occurrence time of the monthly extremes reflected a higher temporal variability of severe dust storms.

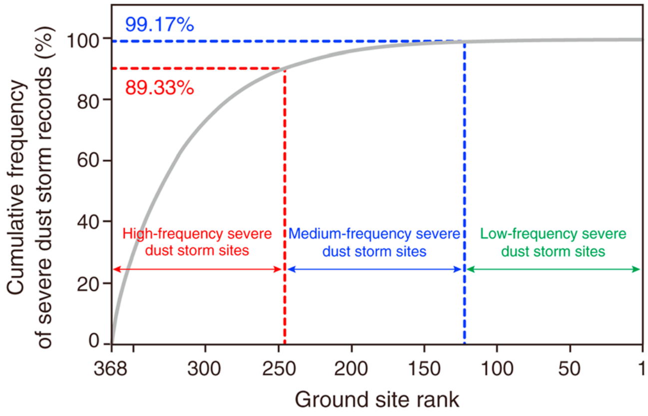

Figure 2. The cumulative frequency of severe dust storm records at 368 meteorological observation sites from 1958 to 2007. The selected sites are ranked from 1 (with the least number of severe dust storm records) to 368 (with the most records). Based on the ranks, the sites are categorized into three groups, including the high-, medium-, and low-frequency severe dust storm sites, corresponding to the intersite ranks from 368 to 246, 245 to 124, and 123 to 1, respectively.

To further understand the cause of the dynamics in the temporal variability, we determined the clustering of severe dust storm activity in time. To do so, we calculated the intermonth standard deviation (SD) of the 10-year averaged monthly relative frequency of severe dust storm records in each decade over the study period. A larger intermonth SD indicated a higher degree of the irregular distribution of severe dust storms at the monthly scale, and likely a higher degree of the clustering of severe dust storm outbreak. In addition to the monthly scale, we calculated the interannual SD of the relative frequency of severe dust storm records in a calendar month against the same month in each decade to assess the temporal stability of the clustering of severe dust storm activity at the annual scale. Severe dust storm records from February to June, when severe dust storms extensively occur in China (Figure 3a), were used for this calculation. A larger averaged interannual SD of the five months indicated a more volatile clustering of severe dust storm activity in this decade.

Moreover, we examined the trend in the timing of the "severe dust storm season." The occurrence of severe dust storms in China shows an apparent

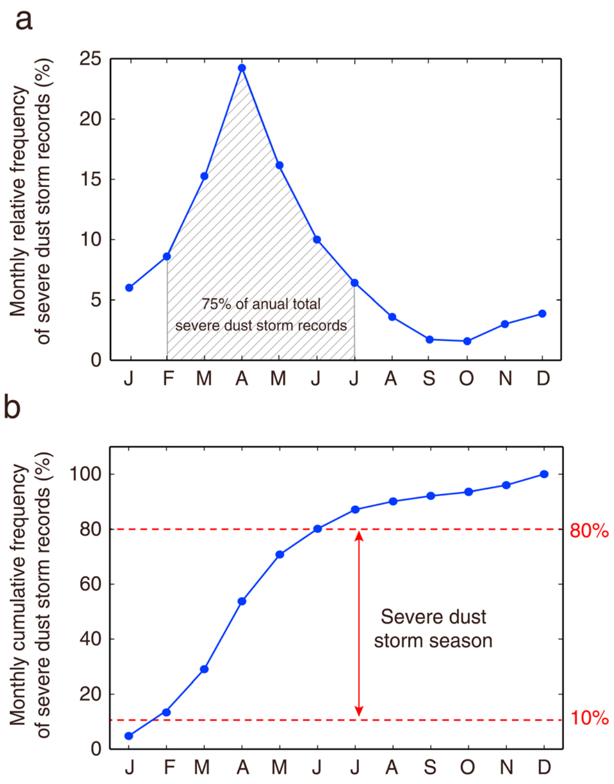

Figure 3. Definition of the severe dust storm season. (a) The monthly relative frequency of severe dust storm records from all of the selected sites during 1958–2007. Shaded area indicates that 75% of the total severe dust storm records intensively take place in five months (February to June). (b) The monthly cumulative frequency of severe dust storm records from all of the selected sites. By the end of February (or June), the accumulative frequency of severe dust storm records reaches 13.45% (or 80.49%). Therefore, this study defines the onset (or end) date of the severe dust storm season as the day on which the number of nation-wide severe dust storm records reaches 10% (or 80%) of the total severe dust storm records in a year.

seasonality. Over the entire study period, 75% of the severe dust storm records were documented between February and June (Figure 3a). According to the accumulative frequency of severe dust storm records (Figure 3b), from 10 to 80% of the total severe dust storm records is the period when the outbreak of severe dust storm concentrates. Thus, we defined the onset and end dates of a severe dust storm season as the day on which the number of nation-wide severe dust storm records reached 10 and 80%, respectively, of the annual total records in that year (Figure 3b). Then, we assessed the temporal evolution of the onset and end dates of the severe dust storm season. A shorter severe dust storm season indicated a higher clustering of severe dust storm outbreak, and thereby a higher temporal variability of severe dust storm occurrence at the monthly scale. Additionally, a larger SD of the onset and end dates of the severe dust storm season in successive years represented a higher temporal variability of severe dust storm occurrence at the annual scale.

Furthermore, we developed a proxy to synthetically quantify the temporal variability of severe dust storms at both the monthly and annual scales. Previous studies calculated the SD of the relative abundance of monthly severe weather records over several years as a measure of the temporal variability of severe weather (e.g., Brooks et al., 2014; Guo et al., 2016). A larger SD of the monthly frequency suggested a higher level of irregular distribution of the monthly severe weather records as well as a higher temporal variability (Brooks et al., 2014; Guo et al., 2016). However, for the severe dust storm data set studied here, the general decreasing trend in the annual frequency may influence the effectiveness of measuring the temporal variability by such an indicator. To offset this potential impact, we calculated the SD of the monthly relative frequency of severe dust storm records at the national scale over a 10-year period (i.e., 10 years × 12 months/year) to quantify the temporal variability (Figure S1a):

$$\mathrm{TV}_{i+5} = \frac{1}{N}\sqrt{\sum_{i=1}^{10}\sum_{j=1}^{12}\left(x_{i,j}-\overline{x}\right)^2}, \tag{1}$$

where TV stands for temporal variability, N is the number of samples in the calculation window (i.e., 120 in this case), and $x_{i,j}$ is the monthly relative frequency of severe dust storm records in the i^{th} year and the j^{th} month. The use of the monthly relative frequency (i.e., the ratio of the number of severe dust storm records in a month to the total number of records in a year) eliminated the influence from the trend in the annual frequency of severe dust storm records. Therefore, the higher the calculated SD is, the more irregular distribution of the severe dust storm occurrence within the 120-month calculation window is, and thereby the more considerable temporal variability of severe dust storms is.

Finally, we determined the days per year with at least one severe dust storm record (named D1) as well as the days per year with at least 15 severe dust storm records (named D15; indicating the occurrence frequency or duration of severe dust storms with a relatively large area of influence) over the entire study period. The relative frequency of D15 (the ratio of D15 to D1) was considered as an indicator of the risk of severe dust storm disaster.

2.4. The Spatial Variability of Severe Dust Storm Occurrence

The spatial variability of severe dust storm occurrence was measured by the variations in the intersite ranking of the severe dust storm frequency, following the method proposed in Guo et al. (2016). More specifically, in each year, the meteorological observation sites were ranked from 1 (with the fewest annual severe dust storm records) to 368 (with the most annual records) across all of the selected sites, with ties assigned to the mean value of the ranks of the ties. At each site, a running SD of its rank was calculated over a 10-year window, indicating the relative variation of severe dust storm records at a given site with respect

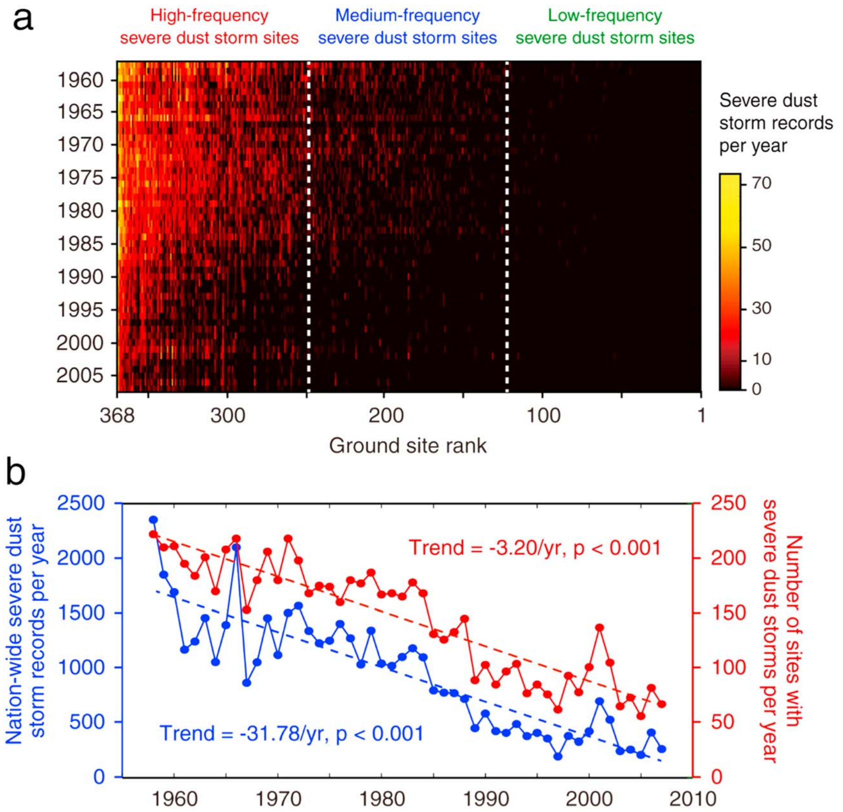

Figure 4. The decreased severe dust storm records during 1958–2007. (a) The annual frequency of severe dust storm records at each meteorological observation site. The vertical dashed lines divide the sites into three groups with different levels of severe dust storm frequency (Figure 2). (b) The long-term trends in the annual frequency of the nation-wide severe dust storm records (indicated by the blue dots) and the number of sites with severe dust storm recorded in each year (indicated by the red dots). The linear fitting lines by the least squares regression are shown with the trends and their significance levels (*p*).

to the remaining selected sites (Figure S1b). Then, the averaged SD across the 368 sites was calculated for each year to quantify the spatial variability:

$$\mathrm{SV}_{i+5} = \frac{\sum_{j=1}^{N} (\frac{1}{10}\sqrt{\sum_{i=1}^{10} (x_{i,j} - \overline{x})^2}}{N}, \tag{2}$$

where SV stands for the spatial variability, *N* is the number of sites (i.e., 368 in this case), and $x_{i,j}$ is the intersite rank of the severe dust storm records for the j^{th} site in the i^{th} year. The higher the averaged SD of the intersite ranks is, the greater the irregular distribution of severe dust storm occurrence in space is, and the higher the spatial variability is. The detailed description of this indicator was provided in Guo et al. (2016).

3. Results

3.1. The Decreased Annual Frequency of Severe Dust Storms

From 1958 to 2007, the annual frequency of severe dust storm records for the most of the selected sites has been declining, except for a spike around the year of 2000 (Figure 4a). At the national scale, annual severe dust storm records have decreased from ~2,000 in the 1950s to ~500 in the 2000s with a dampening rate of 31.78 records per year (Figure 4b). The number of meteorological observation sites with severe dust storm records has declined from over 200 in the 1950s to ~75 in the 2000s at a rate of 3.20 sites per year (Figure 4b). This significantly declining trend in dust storm activity agrees with previous findings in China (e.g., Ding et al., 2005; Fan et al., 2014; Qian et al., 2002; Zhu et al., 2008), which is related to the changes in the large-scale

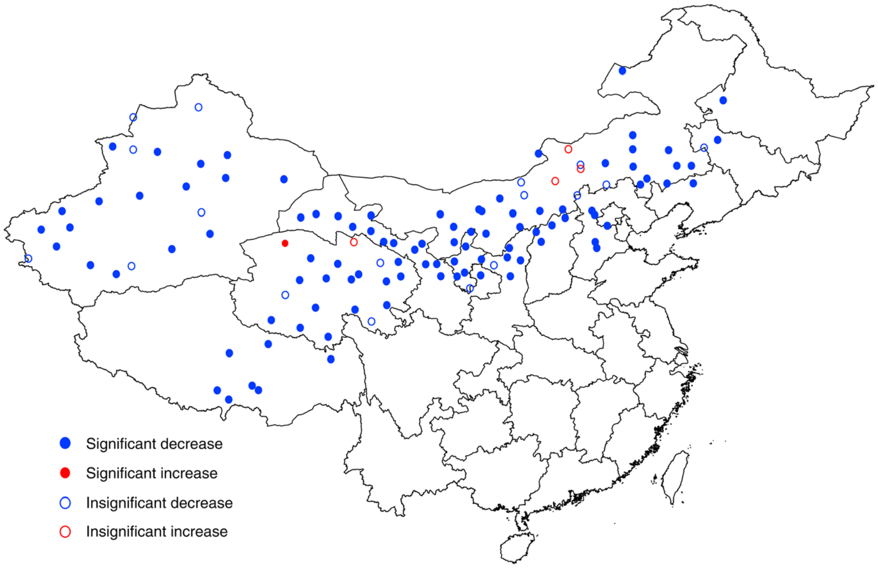

Figure 5. The trends in the annual number of severe dust storm records calculated at each of the high-frequency severe dust storm sites from 1958 to 2007. The blue (red) circle represents a decreasing (increasing) trend. Trends with a significance level of 0.05 are marked with the filled circles.

atmospheric circulation patterns, the local to regional climate conditions, and the soil and vegetation conditions at the ground surface (Li et al., 2015).

For the high-frequency severe dust storm sites, 101 out of 123 sites (i.e., 82%) show a significant decrease in the annual severe dust storm records, whereas only one site demonstrates a significant increase (Figure 5). The other 21 sites show no significant trend. The only site showing an increasing trend is located in the transition region between the Taklimakan desert, Qaidam Basin, and Hexi Corridor (Figures 1 and 5), which is on two major dust storm advance routes in China, i.e., the westward route and the northwestward route (Sun et al., 2001; Wang et al., 2004). It is possible that historically, this site mainly recorded severe dust storm from one dust storm advance route, but now is subjected to severe dust storms from both routes. In addition to the declining trend in the annual frequency of severe dust storm records at the national scale (Figure 4b), Figure 5 suggests that the weakening of the severe dust storm activity occurs in the most of regions in north and northwest China.

3.2. Increased Volatility of the Timing of Severe Dust Storm Occurrence

Apart from the long-term declining trend, variations in severe dust storm occurrence are taking place at the shorter time scales. In the first 15-year period of the data set (1958–1972), the calendar month with the largest number of severe dust storm records is April for 13 years (87% of time), and the month with the least number of records is September or October for 14 years (93% of time); whereas, in the most recent 15-year period of the data set (1993–2007), the occurrence of the monthly maxima in April decreases to 11 years (i.e., a 14% decrease from 87% to 73% of time), and the monthly minima are seen in seven different months (Figure 6a). The increased irregular distribution of monthly extremes indicates that the temporal pattern of severe dust storm occurrence, which used to be more stable, has become nonstationary in recent years (Figure 6a).

Besides the increased variability in the timing of the monthly extremes, the clustering of severe dust storm activity in a year has intensified. For example, the 10-year average monthly relative frequency of severe dust storm records in April has increased from 22% in 1958–1967 to 32% in 1998–2007 (Figure 6b). That means the outbreak of severe dust storms is more concentrating in April. As a result, the intermonth SD of the monthly relative frequency of severe dust storm records has increased from 6.59 to 9.55% over the two periods, suggesting a more irregular distribution of monthly severe dust storm occurrence, i.e., the increased temporal variability at the monthly scale (Figure 6b). Meanwhile, the interannual variations of the monthly relative frequency of severe dust storm records against the same month in following years have increased (indicated by the error bars in Figure 6b), implying a higher temporal variability of severe dust storm occurrence at the

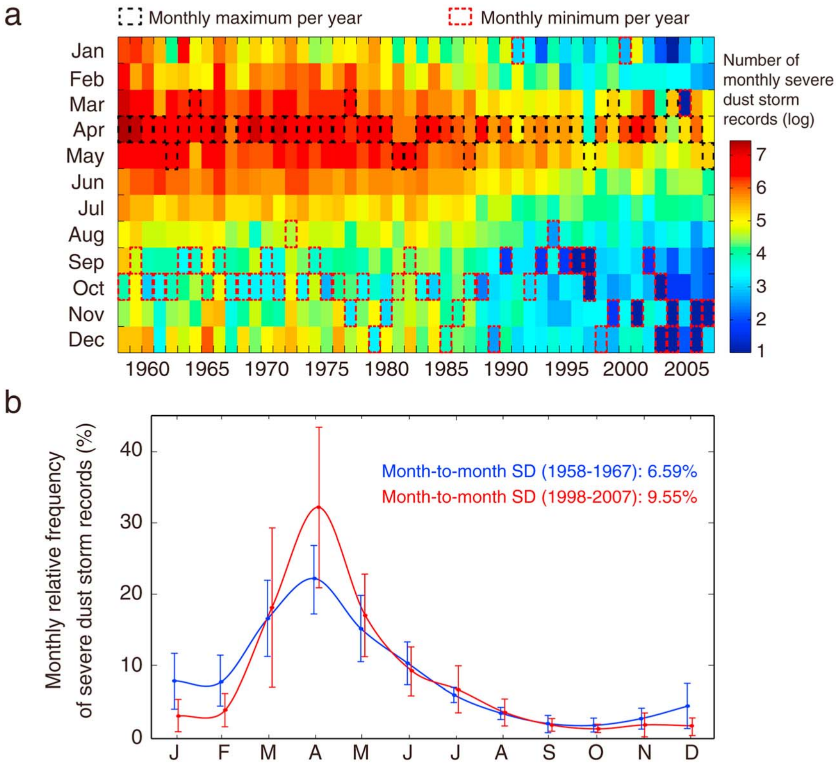

Figure 6. The increased volatility of severe dust storm occurrence over time. (a) Yearly evolution of the nation-wide severe dust storm records at each of the calendar months from 1958 to 2007. The number of monthly severe dust storm records are log transformed. The black (or red) dashed rectangle represents the maximum (or minimum) monthly number of severe dust storm records per year. (b) Temporal clustering of severe dust storm occurrence. The blue (or red) curve indicates the 10-year average monthly relative frequency of severe dust storm records over the period of 1958–1967 (or 1998–2007). The intermonth standard deviation (SD) of the 10-year average monthly relative frequency is shown. Error bars represent the SD of the relative frequency for each calendar month against the same month in 10 years.

annual scale. As an example, the interannual SD of the monthly relative frequency of severe dust storm records in 1958–1967 for March, April, and May (the months with the most frequent severe dust storm occurrence; Figure 3) is 5.08, 4.55, and 4.39%, respectively, which rises to 10.72, 10.81, and 5.60% in 1998–2007, respectively.

Over the entire study period, the intermonth variability of severe dust storm occurrence (calculated as the intermonth SD of the 10-year average monthly relative frequency of severe dust storm records) has kept increasing from 6.97% in 1978–1987 to 7.52% in 1988–1997 and 9.55% in 1998–2007 (Table 1). Moreover,

Table 1
The Increased Temporal Variability of Severe Dust Storm Occurrence as Indicated by the Intermonth Standard Deviation (SD) of the 10-Year Averaged Monthly Relative Frequency of the Nation-Wide Severe Dust Storm Records and the Interannual SD of the Relative Frequency of a Calendar Month Against the Same Month in 10 Years

Period	Intermonth SD of the 10-year average monthly relative frequency of severe dust storm records (%)	Interannual SD of the monthly relative frequency of severe dust storm records in 10 years (%)[a]
1958–1967	6.59	4.06
1968–1977	7.30	3.69
1978–1987	6.97	3.92
1988–1997	7.52	4.87
1998–2007	9.55	6.53

Note. See detailed description of the calculation of the two indicators in the text.
[a] Only severe dust storm records from February to June, the primary period of the severe dust storm season (Figure 3), are used in this calculation.

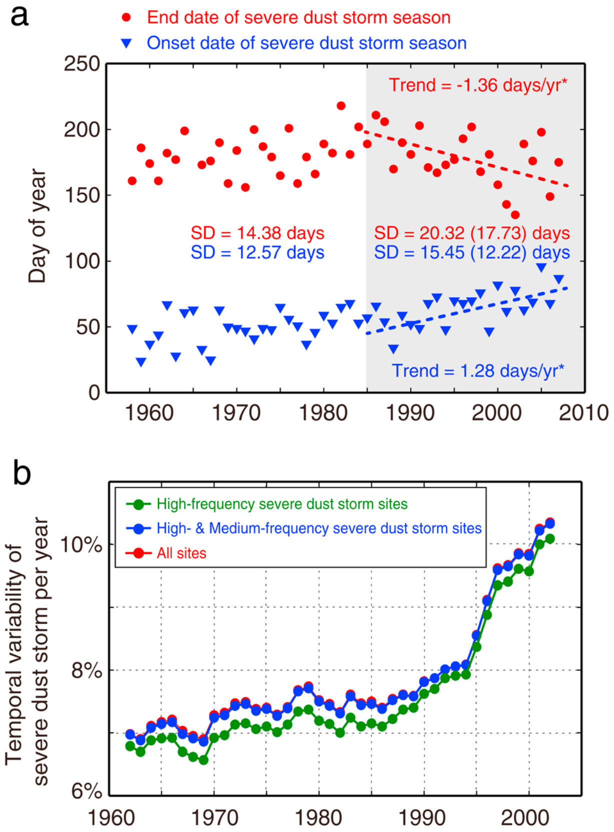

Figure 7. The temporal variability of severe dust storm occurrence. (a) The Julian dates of the onset (blue) and end (red) of the severe dust storm season in each year, 1958–2007. The onset (or end) date of the severe dust storm season is defined as the day on which the number of nation-wide severe dust storm records reaches 10% (or 80%) of the annual total records in each year (Figure 3). The linear fitting lines by the least squares regression are shown with the trends. Asterisk indicates that the significance level of the linear trend is lower than 0.05. The gray shaded area indicates that from 1986 to 2007, severe dust storm season has become shortened, and the standard deviations (SD) of both the onset and end dates have increased as compared to that of 1958 to 1985. Numbers listed in the parentheses are the SD of 1986–2007 calculated after the linear trend is removed. (b) The temporal variability of severe dust storm records for the high-frequency severe dust storm sites (green), high- and medium-frequency severe dust storm sites (blue), and all of the selected sites (red), which is calculated as the SD of the monthly relative frequency of severe dust storm records over a 10-year (or 120-month) period.

the interannual variability of severe dust storm occurrence (calculated as the average interannual SD of the monthly relative frequency of severe dust storm records for 10 years) has kept increasing from 3.69% in 1968–1977 to 3.92% in 1978–1987, 4.87% in 1988–1997, and 6.53% in 1998–2007 (Table 1).

3.3. Increased Variability of the Clustering of Severe Dust Storm Activity

Additional indications of the increased temporal variability can be seen by examining the timing of the severe dust storm season. After 1980, the onset of the severe dust storm season continually delays (at a rate of 1.36 days per year), but the end date continues to advance (at a rate of 1.28 days per year), leading to a shortened severe dust storm season (Figure 7a). From 1986 to 2007, the time window for 70% of the annual severe dust storm to occur (i.e., the severe dust storm season) has shortened by 58.08 days.

Moreover, the times of the onset and end of the severe dust storm season have become more irregular since 1985. From 1958–1985 to 1986–2007, the SD of the onset and end dates of the severe dust storm season has increased from 12.57 to 15.45 days and from 14.38 to 20.32 days, respectively (Figure 7a). Even if the linear trend over 1986–2007 is removed, the SD of the end dates (17.73 days) after 1986 are still larger than that of 1958–1985 (14.38 days). Therefore, the clustering of severe dust storm activity in a year has become more intensified, and the time of clustering has become more nonstationary in following years (Figure 7a).

To comprehensively quantify the dynamics of the temporal variability over time, we calculated the SD of the monthly relative frequency of severe dust storm records over a 10-year period (i.e., 120 months). We find that the temporal variability has increased steadily since 1985 (Figure 7b), which is in line with the dynamics of the severe dust storm season (Figure 7a). Excluding data from the medium- and low-frequency severe dust storm sites shows limited influence, indicating that the high-frequency severe dust storm sites dominate the nation-wide temporal variability of severe dust storm occurrence (Figure 7b). Standard deviations of the monthly relative frequency calculated in other time periods (e.g., 7 and 15 years) also support the increased temporal variability after 1985 (Figure S2). Another measure of the temporal variability based on monthly ranks of severe dust storm records (Brooks et al., 2014; Guo et al., 2016) also demonstrates a similar increasing trend in severe dust storm variability since the 1980s (Figure S3).

To characterize the implication of the clustering of severe dust storm activity, we examined the probability of experiencing a severe dust storm with a large area of influence. During the latest 20-year period of the data set (1988–2007), the averaged days per year with at least one severe dust storm record (D1) have reduced from 153.7 days in 1988–1997 to 118.2 days in 1998–2007, whereas the averaged days per year with at least 15 severe dust storm records (D15) have increased from 2.5 to 4.1 days (Figure 8). The number of days per year with at least 20 severe dust storm records have even doubled from 1.0 to 2.1 days during this period. After being normalized to the same scale, D1 shows a more significant decrease from 1980 to 1994 than D15 does (Figure 8). Therefore, from 1980 to 2007, the number of days per year with many severe dust storm records has increased, with respect to the days with at least one severe dust storm record. This implies that the likelihood of experiencing severe dust storms with a more extensive range of influence has relatively increased. Thus, if a day does have a severe dust storm, there is a higher chance of experiencing a severe dust storm recorded in many sites or a severe dust storm with a relatively vast range of influence (Figure 8).

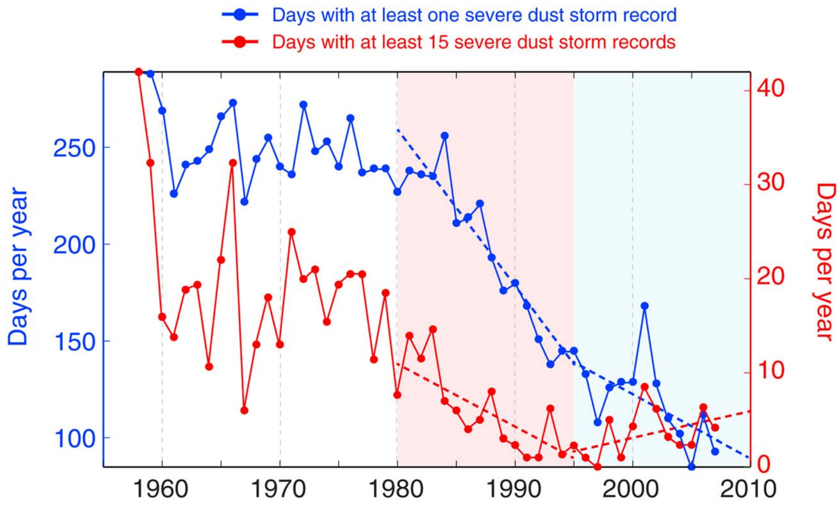

Figure 8. The number of days per year with at least one severe dust storm record (blue dots; named D1) and days per year with at least 15 records (red dots; named D15) from 1958 to 2007. Both D1 and D15 are normalized to their ranges (i.e., from the minimum to the maximum). From 1980 to 1995, D1 shows a greater decreasing trend than that of D15 (as indicated by the red shaded area). From 1996 to 2007, D1 keeps a decreasing trend, whereas D15 shows an increasing trend (as indicated by the blue shaded area). Dashed lines represent the linear fitting lines by the least squares regression.

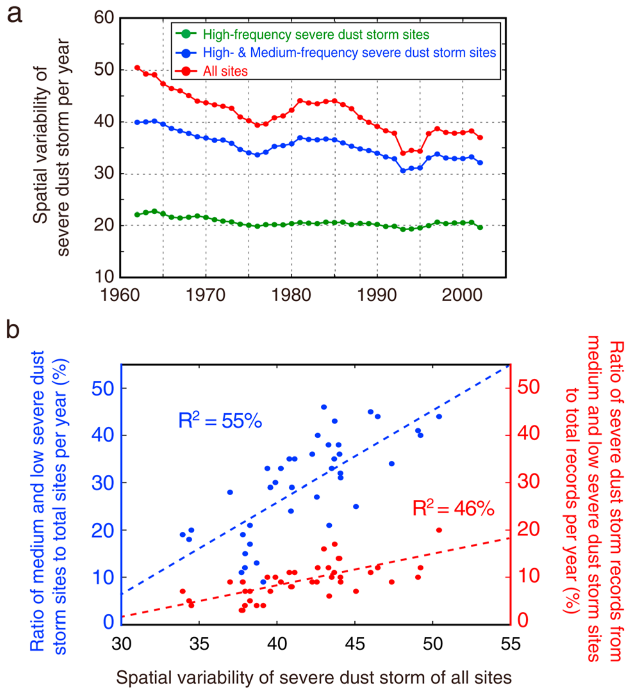

Figure 9. The spatial variability of severe dust storm occurrence over China since the 1960s. (a) Spatial variability of severe dust storm records for the high-frequency severe dust storm sites (green), high- and medium-frequency severe dust storm sites (blue), and all of the selected sites (red), which is calculated as the standard deviation (SD) of the intersite ranking of the severe dust storm over a 10-year period. (b) Linear regressions of the spatial variability of severe dust storm records for all of the selected sites against the ratio of the number of the medium- and low-frequency dust storm sites to the total number of sites with severe dust storm records per year (blue) and the ratio of the number of severe dust storm records from the medium- and low-frequency dust storm sites to the total records per year (red). Coefficients of determination of the linear regressions are shown.

3.4. Spatial Variability of Severe Dust Storm Occurrence

To locate the geographical regions that are most likely to encounter a higher risk of experiencing severe dust storms with a large influence area, we examined the spatial variability of severe dust storm occurrence. If data from all of the selected sites are used, the spatial variability shows an overall decreasing trend (Figure 9a). Similar patterns are identified when the SD of the intersite ranks for each site is calculated for other time periods (e.g., 7 and 15 years; Figure S4).

The nation-wide decreased spatial variability can be explained by the declining severe dust storm records at the medium- and low-frequency severe dust storm sites (Figure 9b). As severe dust storm occurrence has receded to more confined regions (mainly the high-frequency severe dust storm sites), rather than spreading across the country, the stability of the spatial distribution of severe dust storm is consolidated (Figures 4a and 9a). However, if only the high-frequency severe dust storm sites are included, the spatial variability remains relatively consistent since 1975 (Figure 9a). It suggests a stable spatial structure of severe dust storm occurrence among the high-frequency severe dust storm sites. Therefore, due to the spatial clustering of severe dust storm activity to north and northwest China where the high-frequency severe dust storm sites are primarily located (Figure 1), this region likely has a relatively higher risk of experiencing severe dust storms with a large influence area (Figure 8).

4. Discussion

Characterizing the variability of localized severe weather under the large-scale warming climate is of great interest (Brooks et al., 2014; Easterling et al., 2000; Zhang et al., 2017; Zheng et al., 2015). The continuous records of the severe dust storm in China that are documented by professionally trained meteorological observers provide a useful data set to examine the variability of severe weather climatology. To the best of our knowledge, this study presents by far the most holistic analysis of severe dust storm variability in China over an extended period (1958–2007). Based on data from 368 meteorological observation sites across China, we confirm the nation-wide declining trend in severe dust storm activity since the 1950s (Figure 4).

In addition to the trend in annual frequency, the pattern of severe dust storm occurrence has changed in both temporal and spatial variability. We find that the clustering of severe dust storm occurrence in a year has strengthened after 1985 (Figure 7), and the times of the severe dust storm season and the monthly extremes of severe dust storm records have become more volatile (Figures 6 and 7). Because of such a shorter severe dust storm season with irregular occurrence time, the temporal variability of severe dust storm climatology has increased significantly since 1985 (Figure 7b), which was not reported before. Because of the increased clustering in the temporal distribution of severe dust storm activity, there is an increasing trend in the number of days per year with many severe dust storm records from 1980 to 2007 (Figure 8).

Given the spatial clustering of severe dust storm activity to the high-frequency severe dust storm sites located in the north and northwest of China (Figures 4a and 9), our findings suggest the relatively increased risks of severe dust storm-related disasters in north and northwest China since 1980 (Figures 1 and 8). Therefore, although there is a nation-wide decreasing trend in annual severe dust storm records, once a severe dust storm occurs, there is a higher chance that this severe dust storm has a relatively large range of influence (Figure 8). In consequence, more systematic efforts of warning dissemination and disaster mitigation should be paid attention to the areas with historically high severe dust storm frequency in north and northwest China (Figure 1), as the spatial distribution of severe dust storm occurrence remains unchanged among the high severe dust sites (Figure 9).

In May 2017 a severe dust storm, originating from the Gobi desert, impacted large areas of northwest and central China, reaching across Korean Peninsula and Japan (Japan Meteorological Agency, 2017), which supports the outbreak of severe dust storms that have a large influence range. In a related study, Kim (2008) also indicated that the long-range transport of dust from central Asia to South Korea shows an increasing trend from the early 1980s. Moreover, two most recent studies suggested that the dust storms in northern China are likely to be more severe and impact larger areas over the past two decades (Guan et al., 2015; Wang et al., 2017). Therefore, continuous efforts in China are needed to combat desertification and severe dust storms (Middleton, 2016). However, this crucial information is challenging to extract by examining the long-term trend of severe dust storm alone. Hence, we advocate that more research efforts should be pursued to understand the variability of severe weather climatology apart from the long-term trends in annual frequency.

In addition to European cyclones (Pinto et al., 2014), U.S. tornadoes (Elsner et al., 2015; Tippett et al., 2016), and Asian floods (Gu et al., 2016), this study adds new evidence of the increased variability and clustering of severe weather climatology under the warming climate. Synergistic efforts to reduce the risks posed by severe weather, such as the recently established European Union COST Action Network on “Understanding and modeling compound climate and weather events (DAMOCLES),” are essential to human society in the changing climate (Wahl et al., 2018). More research in the future can be done to link severe weather patterns to climate trends in a more global and holistic manner. At this point, it is beyond the scope of the current study to pinpoint a possible physical hypothesis for the intensified clustering of severe dust storm activity in China. It is likely that various factors, such as large-scale atmospheric circulation, regional wind intensity and rainfall pattern, and vegetation coverage change induced by warming and human activity, are involved (Ding et al., 2005; Fan et al., 2014; Li et al., 2015; Qian et al., 2002; Shao & Dong, 2006; Tan & Li, 2015; Zhou & Zhang, 2003). Future weather composite studies can identify favorable synoptic systems that correspond to the days with more severe dust storm records. This knowledge can be utilized to improve severe dust storm modeling and operational dust forecast.

5. Conclusions

Severe dust storms are recognized as of increasing significance in environment and human society at local and global scales. By examining the continuous observation on severe dust storm records at 368 meteorological observation sites across the mainland China from 1958 to 2007, we show that the clustering of severe dust storm outbreak has intensified after 1985. Moreover, the time of the clustering (i.e., the dust storm season) has demonstrated a higher interannual variation over time. As a result, the variability of severe dust storm occurrence has increased significantly at the annual and monthly scales since the 1980s. Along with the increased temporal variability of the severe dust storm activity, the relative probability of experiencing a severe dust storm with a broad range of influence has increased. Spatially, severe dust storm outbreak has receded from spreading across the mainland China in the 1950s to mainly affecting north and northwest China in the 2000s. A relatively higher risk of the severe dust storm disaster in north and northwest China is suggested that is associated with the intensified clustering of severe dust storm activity in both time and space. Findings in this study shed new insights into the variability of the severe weather climatology under the changing climate that can be used to enhance the warning dissemination and mitigation efforts to combat dust storm disasters.

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References

Brooks, H. E., Carbin, G. W., & Marsh, P. T. (2014). Increased variability of tornado occurrence in the United States. *Science*, *346*(6207), 349–352. https://doi.org/10.1126/science.1257460

Ding, R. Q., Li, J. P., Wang, S. G., & Ren, F. M. (2005). Decadal change of the spring dust storm in northwest China and the associated atmospheric circulation. *Geophysical Research Letters*, *32*, L02808. https://doi.org/10.1029/2004GL021561

Easterling, D. R., Evans, J. L., Groisman, P. Y., Karl, T. R., Kunkel, K. E., & Ambenje, P. (2000). Observed variability and trends in extreme climate events: A brief review. *Bulletin of the American Meteorological Society*, *81*(3), 417–425. https://doi.org/10.1175/1520-0477(2000)081<0417:OVATIE>2.3.CO;2

Elsner, J. B., Elsner, S. C., & Jagger, T. H. (2015). The increasing efficiency of tornado days in the United States. *Climate Dynamics*, *45*(3–4), 651–659. https://doi.org/10.1007/s00382-014-2277-3

Fan, B. H., Guo, L., Li, N., Chen, J., Lin, H., Zhang, X. Y., et al. (2014). Earlier vegetation green-up has reduced spring dust storms. *Scientific Reports*, *4*(1), 4. https://doi.org/10.1038/srep06749

Feng, J. L., Li, N., Zhang, Z. T., & Chen, X. (2017). The dual effect of vegetation green-up date and strong wind on the return period of spring dust storms. *Science of the Total Environment*, *592*, 729–737. https://doi.org/10.1016/j.scitotenv.2017.02.028

Goudie, A. S. (2009). Dust storms: Recent developments. *Journal of Environmental Management*, *90*(1), 89–94. https://doi.org/10.1016/j.jenvman.2008.07.007

Gu, X. H., Zhang, Q., Singh, V. P., Chen, Y. D., & Shi, P. J. (2016). Temporal clustering of floods and impacts of climate indices in the Tarim River basin, China. *Global and Planetary Change*, *147*, 12–24. https://doi.org/10.1016/j.gloplacha.2016.10.011

Guan, Q. Y., Yang, J., Zhao, S. L., Pan, B. T., Liu, C. L., Zhang, D., & Wu, T. (2015). Climatological analysis of dust storms in the area surrounding the Tengger desert during 1960–2007. *Climate Dynamics*, *45*(3–4), 903–913. https://doi.org/10.1007/s00382-014-2321-3

Guo, L., Wang, K. C., & Bluestein, H. B. (2016). Variability of tornado occurrence over the continental United States since 1950. *Journal of Geophysical Research: Atmospheres*, *121*, 6943–6953. https://doi.org/10.1002/2015JD024465

He, Y., Zhao, C., Song, M., Liu, W., Chen, F., Zhang, D., & Liu, Z. (2015). Onset of frequent dust storms in northern China at ~AD 1100. *Scientific Reports*, *5*(1). https://doi.org/10.1038/srep17111

Japan Meteorological Agency (2017). Aeolian Dust Information (Observation). Retrieved from http://www.jma.go.jp/en/kosa/

Kim, J. (2008). Transport routes and source regions of Asian dust observed in Korea during the past 40 years (1965–2004). *Atmospheric Environment*, *42*(19), 4778–4789. https://doi.org/10.1016/j.atmosenv.2008.01.040

Li, G. J., Chen, J., Ji, J. F., Yang, J. D., & Conway, T. M. (2009). Natural and anthropogenic sources of east Asian dust. *Geology*, *37*(8), 727–730. https://doi.org/10.1130/G30031A.1

Li, N., Guo, L., & Fan, B. (2015). A new perspective on understanding the reduced spring dust storm frequency in Inner Mongolia, China. *International Journal of Disaster Risk Science*, *6*(3), 216–225. https://doi.org/10.1007/s13753-015-0062-5

Liu, X. D., Yin, Z. Y., Zhang, X. Y., & Yang, X. C. (2004). Analyses of the spring dust storm frequency of northern China in relation to antecedent and concurrent wind, precipitation, vegetation, and soil moisture conditions. *Journal of Geophysical Research*, *109*, D16210. https://doi.org/10.1029/2004JD004615

Meehl, G. A., Zwiers, F., Evans, J., Knutson, T., Mearns, L., & Whetton, P. (2000). Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change. *Bulletin of the American Meteorological Society*, *81*(3), 427–436. https://doi.org/10.1175/1520-0477(2000)081<0427:Tiewac>2.3.Co;2

Middleton, N. (2016). Rangeland management and climate hazards in drylands: Dust storms, desertification and the overgrazing debate. *Natural Hazards*, 1–14. https://doi.org/10.1007/s11069-016-2592-6

Middleton, N. J. (1986). A geography of dust storms in Southwest Asia. *Journal of Climatology*, *6*(2), 183–196. https://doi.org/10.1002/joc.3370060207

Pinto, J. G., Gomara, I., Masato, G., Dacre, H. F., Woollings, T., & Caballero, R. (2014). Large-scale dynamics associated with clustering of extratropical cyclones affecting Western Europe. *Journal of Geophysical Research: Atmospheres*, *119*, 13,704–13,719. https://doi.org/10.1002/2014JD022305

Qian, W. H., Quan, L. S., & Shi, S. Y. (2002). Variations of the dust storm in China and its climatic control. *Journal of Climate*, *15*(10), 1216–1229. https://doi.org/10.1175/1520-0442(2002)015<1216:Votdsi>2.0.Co;2

Shao, Y., & Dong, C. H. (2006). A review on east Asian dust storm climate, modelling and monitoring. *Global and Planetary Change*, *52*(1–4), 1–22. https://doi.org/10.1016/j.gloplacha.2006.02.011

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*, *106*, 10325–10333. https://doi.org/10.1029/2000JD900665

Tan, M. H., & Li, X. B. (2015). Does the green Great Wall effectively decrease dust storm intensity in China? A study based on NOAA NDVI and weather station data. *Land Use Policy*, *43*, 42–47. https://doi.org/10.1016/j.landusepol.2014.10.017

Tippett, M. K., Lepore, C., & Cohen, J. E. (2016). More tornadoes in the most extreme US tornado outbreaks. *Science*, *354*(6318), 1419–1423. https://doi.org/10.1126/science.aah7393

Wahl, T., Ward, P. J., Winsemius, H. C., AghaKouchak, A., Bender, J., Haigh, I. D., et al. (2018). When environmental forces collide. *Eos*, *99*. https://doi.org/10.1029/2018EO099745

Wang, R. X., Liu, B., Li, H. R., Zou, X. Y., Wang, J. P., Liu, W., et al. (2017). Variation of strong dust storm events in northern China during 1978–2007. *Atmospheric Research*, *183*, 166–172. https://doi.org/10.1016/j.atmosres.2016.09.002

Wang, X. M., Dong, Z. B., Zhang, J. W., & Liu, L. C. (2004). Modern dust storms in China: An overview. *Journal of Arid Environments*, *58*(4), 559–574. https://doi.org/10.1016/j.jaridenv.2003.11.009

Zhang, Q. H., Ni, X., & Zhang, F. Q. (2017). Decreasing trend in severe weather occurrence over China during the past 50 years. *Scientific Reports*, *7*(1). https://doi.org/10.1038/srep42310

Zheng, G. J., Duan, F. K., Su, H., Ma, Y. L., Cheng, Y., Zheng, B., et al. (2015). Exploring the severe winter haze in Beijing: The impact of synoptic weather, regional transport and heterogeneous reactions. *Atmospheric Chemistry and Physics*, *15*(6), 2969–2983. https://doi.org/10.5194/acp-15-2969-2015

Zhou, B. Z., Gu, L. H., Ding, Y. H., Shao, L., Wu, Z. M., Yang, X. S., et al. (2011). The great 2008 Chinese ice storm: Its socioeconomic-ecological impact and sustainability lessons learned. *Bulletin of the American Meteorological Society*, *92*(1), 47–60. https://doi.org/10.1175/2010bams2857.1

Zhou, Z. J., & Zhang, G. C. (2003). Typical severe dust storms in northern China during 1954–2002. *Chinese Science Bulletin*, *48*(21), 2366–2370. https://doi.org/10.1360/03wd0029

Zhu, C. W., Wang, B., & Qian, W. H. (2008). Why do dust storms decrease in northern China concurrently with the recent global warming? *Geophysical Research Letters*, *35*, L18702. https://doi.org/10.1029/2008GL034886

Zou, X. K. K., & Zhai, P. M. M. (2004). Relationship between vegetation coverage and spring dust storms over northern China. *Journal of Geophysical Research*, *109*, D03104. https://doi.org/10.1029/2003JD003913