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Regional characteristics of three kinds of dust storm events in China

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Abstract

The regional characteristics of dust storm events including dust storm, blowing dust and floating dust in China have been studied by using the data from 701 meteorological observation stations during 1954–2000. The results are as follows: in China, there are two main areas (the South Xinjiang Region and the Hexi Region) where dust storm events happen the most frequently. The spatial distributions of the three types of dust storm events are different. Dust storms mainly occur in the arid and semiarid areas in Northern China. Blowing dust and floating dust not only occur in those areas, but also in neighboring areas. Compared with dust storm and blowing dust, the floating dust very seldom occurs in high-latitude areas. The frequencies of dust storm events decreased generally during 1954–2000. However, they have gradually increased since 1998. The interannual variations of dust storm events showed some characters including two cycles of 3–4 and 11–12 years. The annual changes of the dust storm events were characterized by a strong unimodal distribution with spring maximum. The daily variation of the dust storm occurrence was remarkable, most of dust storms happened in the afternoon, especially between 18:01–21:00 LST. The areas of dust storms could be divided into seven sub-regions. The most frequent areas of dust storms and floating dust were in the South Xinjiang Region, but that of blowing dust was in the Hexi Region. Their maximum interannual variance also happened in both areas. Dust storm events generally occurred most frequently in April in most parts of China, but it happened a little earlier in the Qinghai-Xizang Region and a little later in the Xinjiang Region. The months in which dust storm events occurred more frequently were relatively concentrated in the Northeastern Region and Hetao Region, but were relatively dispersed in the Xinjiang Region.

Keywords: Dust storm events; Regional characteristic; Spatial distribution; Temporal distribution

1. Introduction

Dust storm events, especially strong dust storms are not only immediately dangerous, but may also have a long-term, harmful effect. They severely destroy the original area's atmospheric environment and ecological environment including vegetation and soil and can accelerate desertification by sand burying and blowing. Additionally, the dust aerosols carried by dust storm events have affected local climate by decreasing atmospheric visibility, and by influencing the radiation balance of the atmosphere (Tegen and Fung, 1994,

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1995; Tegen et al., 1996; Li et al., 1996; Andreae, 1996). They can also modify atmospheric optical features, so as to disrupt the natural ecological environment. Furthermore, it has been observed that the long-range transport of mineral aerosols caused by dust storm plays an important role in mesoscale to macroscale and even global climatic modification (Idso, 1974; Idso and Brazel, 1977; Littmann, 1991). It is not only a significant symptom of the desertification from slower to faster change, but also a reflection of the synthesis of environmental states, including climate, ecosystem and soil, which are all deteriorating to some degree. Therefore dust storm events have become an important environmental problem paid attention to by more and more people in the world. So, understanding and predicting dust storm events have been a scientific and social problem of consequence.

According to the definition of Meteorological Observing Criterion from the National Weather Bureau of China (1979), dust storms, blowing dust and floating dust belong to a category called dust storm events. Among them, the dust storm is the severest in three kinds of dust storm events and generally defined as a storm that carries a great deal of dust and sand lofted by strong wind. It is a disastrous weather event which makes air quite turbid and lowers horizontal visibility to <1000 m. An intense dust storm with maximal destructive power can reduce surface horizontal visibility to <50 m, even to 0 m, and is then called a ''Black Storm''. Blowing dust is stronger in three kinds of dust storm events and is generally defined as a weather phenomenon which is formed by big winds carrying a lot of dust and sand, and can reduce horizontal visibility to 10,000–1000 m. Floating dust is the weakest in three kinds of dust storm events and is generally defined as another weather phenomenon in which fine dust is suspended in the lower troposphere with horizontal visibility of $<10{,}000$ m. It occurs usually when dust is transported by air flow of the mid and upper troposphere from an upwind place, or there are some fine dust still suspended in air after a dust storm happened.

The Northern China is a part of one of four frequent occurrence regions of dust storm in the world (Yan, 1993), and is located in the East Asian monsoon region where arid and semiarid climates dominate. In this region, the total area of Gobi (gravel), deserts and desertification land is approximately 1.653 million km^2 (Wang and Zhu, 2001). A great deal of eolian dust entrained from the deserts of west China not only influence inland China but can be remotely transported to Japan, Korea (Chun et al., 2002), and even America (Uematsu et al., 1983; Uno et al., 2001; Tratt et al., 2001). The investigation of spatial and temporal distribution characteristics of dust storms is a basis of studying dust storms. An effort has been made to study spatial distribution characteristics of dust storms in South and Central America and in the Sahara Desert of Africa since the 1930s. The distribution of dust storms in Mexico City was systematically studied (Jauregui, 1989); the spatial and temporal distribution of dust storm caused by wind erosion in the United States was also investigated by Gillette and Hanson (1989); those of dust storm occurrence in the US state of New Mexico was studied by using detailed observed data (Snow and McClelland, 1990). In China, our scholars have been studying dust storms since the 1970s (Xu et al., 1979), and have preliminarily found out spatial and temporal distribution characteristics, source area and moving paths of dust storms in China (Littmann, 1991; Wang et al., 1996; Xu and Hu, 1997; Zhou, 2001; Qiu et al., 2001; Qian et al., 2002a). However, on the one hand previous investigations about dust storm events were only limited to dust storm; on the other hand, there was not as many data used as this paper. Concerning blowing dust and floating dust, especially regional characteristics of dust storm events few investigations have been carried out in China. On the basis of data collected from 701 observation stations in China during 1954–2000, this paper emphasizes the analyses of regional characteristics of dust storms, blowing dust and floating dust in China, so that a scientific basis can be provided for preventing or reducing their disastrous consequences.

2. Data and methods

2.1. Data

For this investigation, the data have been used, including occurrence days of dust storms, blowing dust and floating dust, which compiled from 701 meteorological observing stations during 1954–2000 (during 1951–1953, the observational standards of dust-storm events' data were different from that in 1954 and afterwards, and the numbers of observing stations were fewer. Therefore, we omitted the data during 1951–1953. In addition, because of rare observing stations and incomplete data in southwestern Qinghai-Xizang Region, this area has not been analyzed yet). The monthly occurrence days of dust storm, sand storm and floating dust were regarded as quantitative token indices. All of these data came from the National Center for Climatological Data in Beijing.

In order to more comprehensively study dust storms in source places, we have used daily observational data of dust storms in Minqin from 1954 to 2000 and in Minfeng from 1961 to 2000.

2.2. Methods

A method of clustered analysis was used to investigate the division of dust storm events in China. The occurrence days and time of dust storms were regarded as main factors. We used the stratified cluster method, whose principle is that the approaches of their variation are clustered into one kind. Practical steps were: (1) the original data were standardized; (2) each variable was looked on as one kind and correlation coefficients were calculated; (3) two variables were united into a new kind according to the maximum correlation coefficient; (4) the correlations between new kinds and other kinds were calculated; and (5) steps (2)–(4) were repeated until all kinds were united into one major kind. To study the changes of dust storm events in each region, a mean interannual variability was calculated. Expressions of mean interannual variation:

$$\text{mean interannual variability} = \frac{1}{n-1}\sum_{i=1}^{n-1}(D_{i+1} - D_i),$$

where D_i is the annual occurrence days of any type of dust storm events observed at some meteorological observing station in a certain year, n is the number of years, $i = 1, 2, 3, \ldots, n-1$. The unit is days per year. In addition, the occurrence days of dust storm events in the whole country had been standardized before the variance was calculated. The power spectrum analysis is the frequency domain analysis method based on the Fourier transformation, which purpose is to obtain the main frequency of the period or explicit period implied by the sequences. Practical steps were (1) the self-correlation coefficient is calculated; (2) the estimation value of roughness spectrum is calculated; (3) the estimation value of smoothing spectrum is calculated; (4) the period is determined; (5) the significance test to the estimation value of the spectrum. In this paper, the methods of standardization, calculation of variance, power spectrum analysis and correlation coefficient were utilized from *The Methods of Statistical Analysis and Forecasting in Meteorology* (Huang, 1979).

3. Spatial and temporal distribution characteristics of dust storm events

3.1. Spatial distributions of various types of dust storm events in all of China

It has statistically been analyzed that the data came from all monthly occurrence days of dust storm events, which were derived from 701 meteorological observing stations in China during 1954–2000. And the spatial distribution charts (Fig. 1) have been drawn. To reveal further the spatial distribution differences among these three types of dust storm events, we drew the spatial distribution of the areas in which only the blowing dust or floating dust occurred without the occurrences of dust storms (Fig. 2).

Fig. 1a shows that the spatial distribution of the *dust storms* is basically similar to that of the desert and desertification lands (Zhu and Chen, 1994). This reflects that both the surface states and the distributions of dust sources play an important role in the formation of dust storms. Fig. 1a also indicates that the areas where 47-year mean annual occurrence days of dust storms are more than 10 days are located in South Xinjiang Basin, Hexi Region and northeastern Qinghai-Xizang Plateau, which all lie in the deserts and the borders near them. Of these three areas, the maximum center of the 47-year mean annual occurrence days of dust storms was 35.8 days and located at Minfeng (37°04′N, 82°43′E) in the South Xinjiang Basin. The second most region with 28.1 days was at Minqin (38°38′N, 103°05′E) in the north-eastern Hexi Region. Additionally, the maximum number of dust storms was 62 days in 1962 in Minfeng and 58 days in 1963 in Minqin, respectively. It is reported that the Tarim basin seems to have more dust storms than any other locations on the Earth (Kes and Fedrovich, 1976). Another source of high frequency of dust storms in Central Asia is located over the desert in Mongolia (Natsagdorj et al., 2003). The dust over Japan and Korea has its main source in the region between 35–50°N and 100–110°E and 80–90°E. This area includes the dessert and Gobi of China and Mongolia (Chun et al., 2002). The Taklimakan desert also is an important dust provenance of the eolian dust in the remote North Pacific Ocean (Sun et al., 2001).

Fig. 1b shows that the spatial distribution of frequent occurrence areas of *blowing dust* is basically consistent with that of dust storms, and the frequent occurrence areas are also in the South Xinjiang Basin and Hexi Region. However, the 47-year mean occurrence days of the blowing dust increase remarkably compared with dust storms. For example, there are 81.1 (versus 35.8 days) days per year at Minfeng of South Xinjiang Basin and 96.2 days per year at Jilantai (39°50′N, 105°24′E) in the Hexi Region; And the frequencies of the two frequent occurrence centers are more than that of dust storms with the maximum 150 days in 1966 at Minfeng, and 170 days in 1966 at Jilantai, respectively. In addition, the spatial distribution range of blowing dust extended eastwards noticeably to Northeast China and the East China Plain, and southeastwards to the Yangtze Valley beyond the areas where the dust storms occurred (Fig. 2a).

In comparison with dust storms and blowing dusts, the mean annual occurrence days of the *floating dust* is the most (Fig. 1c); for example, the 47-year mean occurrence days of the floating dust is 208 days at Hetian (37°08′N, 79°56′E) of South Xinjiang Basin and is 70 days at Jilantai of Hexi Region per year. At Hetian of the South Xinjiang Basin, the maximum of floating dust was 302 days in 1985. While at Jilantai of the Hexi Region, the maximum was 170 days in 1979. It is

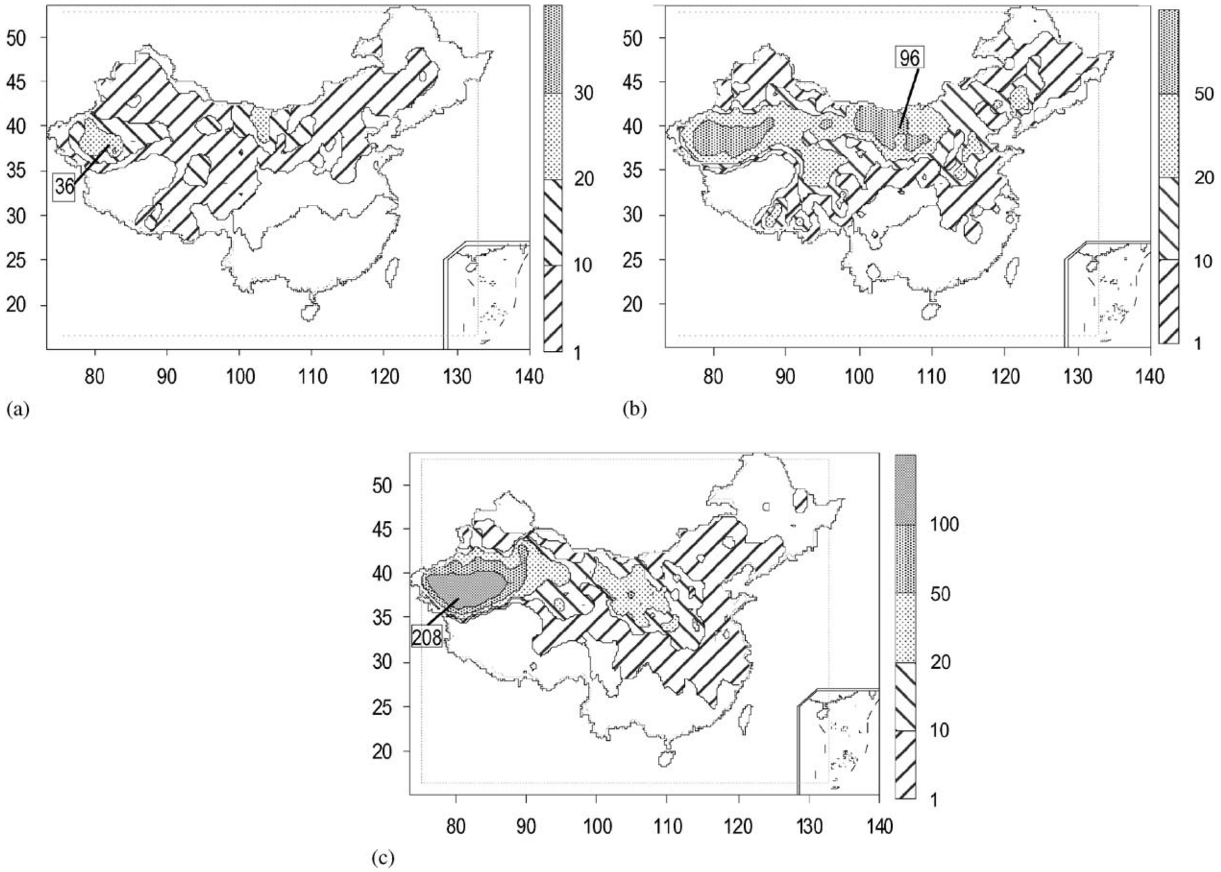

Fig. 1. Spatial distribution of 47-year mean annual occurrence days of (a) dust storms, (b) blowing dust and (c) floating dust in China during 1954–2000. (Label ''Latitude'' along the ordinate and ''Longitude'' along the abscissa. Define the shadings in the vertical bar.)

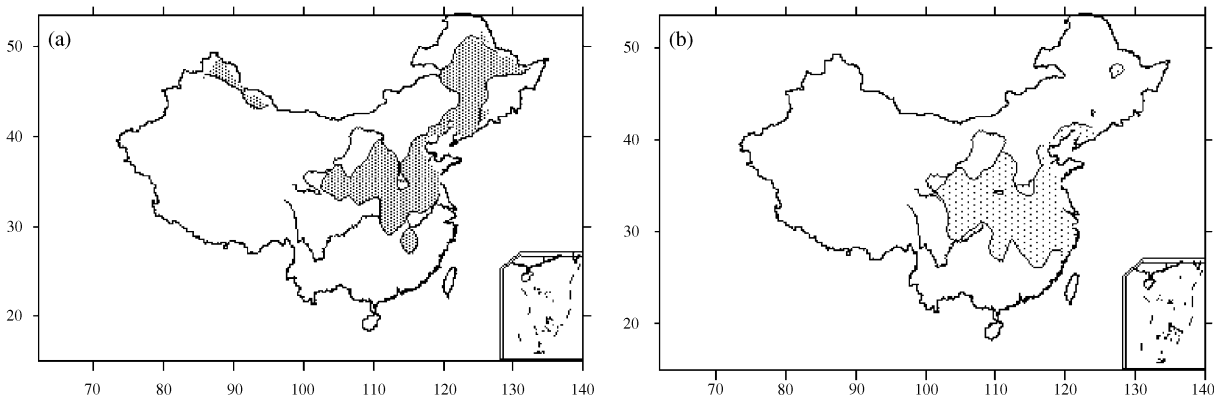

Fig. 2. Spatial distribution of the areas in which (a) blowing dust and (b) floating dust occurrence without dust storms in China during 1954–2000. (Heavy shading represents blowing dust occurrence area without dust storms. Light shading represents floating dust occurrence area without dust storms.)

obviously seen by comparing both Figs. 1a and c with Fig. 2b carefully that floating dust very seldom occurred in the high-latitude areas such as North Xinjiang and Northeast China. Furthermore, the influenced range of the floating dust mainly extended southeastward to the lower-latitude regions such as the East China Plain and

Table 1
Ratio of the number of stations where dust storms occurred among all stations in each ages in China (%)[a]

	1950s	1960s	1970s	1980s	1990s
$1 \leqslant D < 10$	29.67	26.53	23.10	20.92	13.19
$10 \leqslant D < 20$	7.02	5.66	5.99	3.58	2.10
$D \geqslant 20$	5.58	2.38	2.78	1.58	0.15
Total	42.27	34.87	31.87	26.08	15.44

[a] D is days of dust storm occurrence.

the area of the middle and lower reaches of the Yangtze River. This shows that dust storms and blowing dusts harmed their local areas, and the dust swept off by them could be transported to downwind regions, where floating dust formed and affected larger area. However, the frequency of floating dust is lower than the other dust storm events in southeastern Xizang plateau. It may be caused by some special geographical conditions.

The interdecadal change characters of distribution of dust storm are in evidence and are presented in Table 1. Since the 1950s, the stations of total dust storms occurrence have shown a decreasing trend with a maximum in 1950s (42.27%), lower in 1960s (34.87%) and a minimum in 1990s (15.44%). However, the interdecadal change of distribution of higher frequent dust storms (days per year $\geqslant 10$) was different from that of total, and the second maximum of interdecadal change of distribution of frequency more than 10 days was in 1970s.

3.2. Regional division of dust storm events

It is necessary that the dust storm events be divided and studied according to their regional characteristics, since their spatial distributions are closely associated with vegetation coverage, specific geographical conditions, surface ecological environmental status, and synoptic and climatic systems, etc. The regions of desert and desertification lands in northern China were divided into six sub-regions, and it is certain that there were some differences of temperature, precipitation and humidity among these six sub-regions (Shang et al., 2001). These results provided an important basis for the division of dust-storm events. Additionally, two conceptions need to be clarified: one is the source areas of dust-storm events that are mainly located areas where higher frequency of dust storms occur; the other is the influenced areas of dust storm events that are the areas only directly affected to some extent by blowing dust and/or floating dust where dust storm seldom occur. According to the days and time of occurrences of dust storms in the last 47 years, the division of dust storm events was done by means of cluster analysis. The

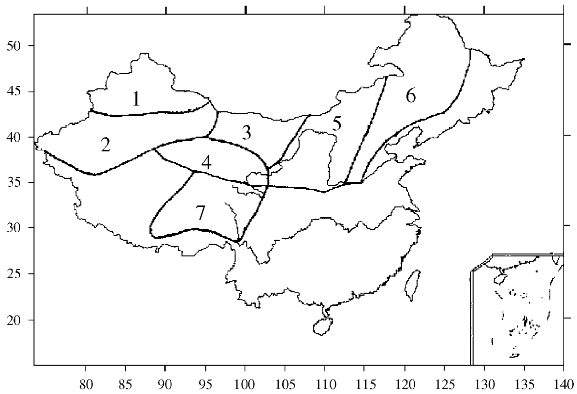

Fig. 3. The diagram of divisional distributions of the areas where dust storms occur frequently in China. (Label "Latitude" along the ordinate and "Longitude" along the abscissa.)

separated results are as follows: the Xinjiang Region is divided by the Tianshan Mountain Range into the North Xinjiang Region and the South Xinjiang Region; both the Hexi Region and the Hetao Region are divided by the Helan Mountain Range which are generally regarded as the edge line between arid and semiarid areas; both the Hetao Region and the Northeastern China Region are divided by the Taihang Mountain Range which are generally regarded as the edge line between semiarid and sub-humid areas. In addition, the Qaidam Basin Desert is separated from Qinghai-Xizang Plateau. Thus, the areas of dust storm events in China are divided into seven sub-regions (Fig. 3): (1) the North Xinjiang Region/(from the north side of the Tianshan Mountain Range to the south side of the Aertai Mountain Range, including the Gurbantunggut Desert); (2) the South Xinjiang Region/(including Taklimakan Desert, Kumtag desert and its neighboring areas); (3) the Hexi Region/(from the north side of the Qilianshan Mountain Range to the west side of the Helan Mountain Range, including Badain Jaran Desert and Tengger Desert); (4) the Qaidam Basin Region/(from the south side of the Qilianshan Mountain Range to the north side of the Bayan Xar Mountain Range, including the Qaidam Desert); (5) the Hetao Region/(from the east side of the Helan Mountain Range to the west side of the Taihang Mountain Range, including the Ulan Bhu Desert, the Hobq Desert and the Mu Us Desert); (6) Northeastern China Region/(from the east side of the Taihang Mountain Range to semiarid areas in Northeastern China, including the sandy lands of Hunshangdake, Horqin and Hulunguir); (7) Qinghai-Xizang Region/(from southern Qinghai to northeastern Xizang, including from southern the Bayan Xar Mountain Range to the northern Himalayas). The divisions of dust storm events are basically consistent with the normally accepted divisions of climate in China (Tao, 1949; Ci and Wu, 1997).

3.3. Temporal distribution

According to national average *interannual* change (Fig. 4), the days of the dust-storm event's occurrence showed a decreasing trend with fluctuation in China from 1954 to 2000. The highest frequency of dust storm events occurred in the mid-1950s. The maximum mean days of dust storm and blowing dust was 4.34 days in 1954, and 16.66 days in 1955 respectively. There was a decrease in the pre-1960s. Then it began to increase. A decreasing trend was shown from 1980s again, until the occurrence days of dust storm events had dropped to the least in 1997 (dust storm, blowing dust, and floating dust was 0.47 days, 3.1 days, and 2.77 days, respectively). Since 1998 its trend has been increasing gradually. However, the mean days of dust storm events decreased to the minimum in 1990s. This result is consistent with the interannual change of dust storm events within the 45-year period of study (Zhou, 2001; Qian et al., 2002b). In contrast with Korea from 1915 to 2000, the maximum number of dust storm events is 14 days in 1993 and the occurrence of dust storm events found to be more frequent during the last decade (Chun et al., 2002).

The periodicity of dust storm was analyzed by using power spectrum analysis from 1954 to 2000 in China. The result indicated that there exists a cyclical pattern including a short period of 3–4 years and a long period of 11–12 years. Additionally, the long period of 11–12 years corresponds with 11-year period of sunspot activity, and the short period corresponds with the period of ENSO (El Niño and Southern Oscillation; Wei, 2002). Ye et al. now claim the higher frequency of dust storms in China was associated with the La Niña phenomenon in 2000 (Ye et al., 2000).

The annual variation of dust storm events is shown in Fig. 5. It is characterized by a strong unimodal distribution with spring maxima in China. In contrast, Yuma and Winslow display bimodal patterns with peaks in April and midsummer; while in Phoenix and Tucson, dust storms are most frequent in the summer (Nickling and Brazel, 1984), and in Bust and Faizabad of Afghanistan, they peak in the summer (Middleton, 1986).

For a study of the *daily* variations of dust storms, we have carried out statistical analyses by using the data of duration and beginning of dust storm events in Minqin and Minfeng, which are two centers of the higher frequency of dust storm occurrence in China. The statistical results are shown at Tables 2–5.

Comparing Table 2 with Table 4, we can find out that the duration of dust storms occurring in Minfeng of the

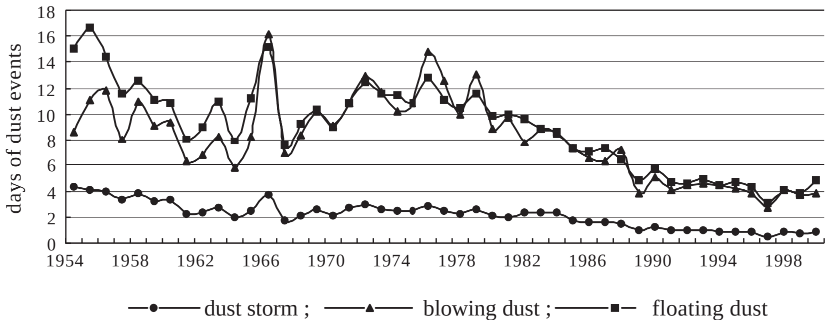

Fig. 4. Interannual variation of annual occurrence days of three kinds of dust storm events in China during 1954–2000.

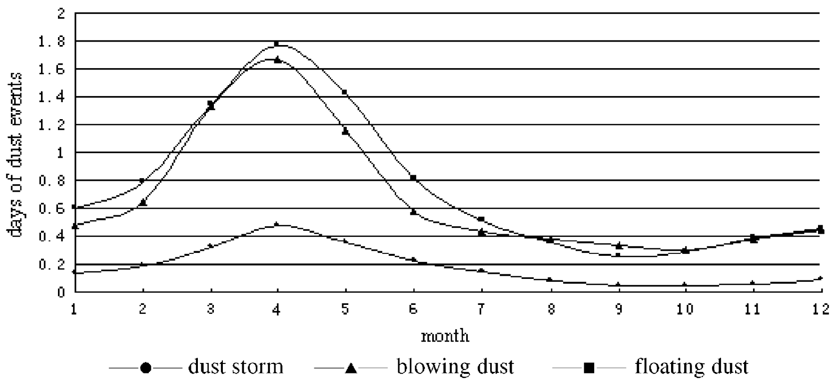

Fig. 5. Annual variation of mean monthly occurrence days of dust storm events in China during 1954–2000.

Table 2
Temporal statistical characteristics of dust storm duration in Minqin of the Hexi Region during 1954–2000

Item	Duration of dust storm (min)					
	0–120	121–240	241–360	361–480	481–600	>600
The number of dust storm occurrence	917	305	119	61	23	11
Frequency (%)	63.9	21.2	8.3	4.3	1.6	0.8

Table 3
Temporal statistical characteristics of dust storm beginning in Minqin of the Hexi Region during 1954–2000

Item	Time interval (h)							
	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
The number of dust storm occurrence	70	55	119	199	264	277	436	66
Frequency (%)	4.9	3.8	8.3	13.9	18.4	15.8	30.4	4.6

Table 4
Temporal statistical characteristics of dust storm duration in Minfeng of the South Xinjiang Region during 1961–2000

Item	Duration of dust storm (min)					
	0–120	121–240	241–360	361–480	481–600	>600
The number of dust storm occurrence	709	321	181	95	49	41
Frequency (%)	50.8	23.0	13.0	6.8	3.5	2.9

Table 5
Temporal statistical characteristics of dust storm beginning in Minfeng of the South Xinjiang Region during 1961–2000

Item	Time interval (h)							
	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
The number of dust storm occurrence	95	94	182	263	88	106	395	173
Frequency (%)	6.8	6.7	13.1	18.8	6.3	7.6	28.3	12.4

South Xinjiang region is longer than that in Minqin of the Hexi region in general. Among them, the duration of 50.8% dust storms in Minfeng was within two hours, while the duration of more than 63% dust storms in Minqin was within two hours. In addition, the duration of dust storms more than 10 h was 2.9% in Minfeng, but in Minqin it was only 0.8%.

Tables 3 and 5 show that the daily variations of dust storm beginning are evident in Minfeng and Minqin. Most of dust storms happened in the afternoon, 64.55% (42.2%) of them occurred during 12:01–21:00 LST; about 30% dust storms occurred between 18:01–21:00 LST, after that time the frequency of dust storm occurrence decreased quickly. This phenomenon shows that thermal instable condition plays an important role in the formation of dust storm. On comparing Table 3 with Table 5, a difference between two places is found out that the daily variations of dust storm beginning in Minqin is single cycle, but in Minfeng there is double cycles, namely there is a second peak value of frequency of dust storm occurrence during 9:01–12:00 LST before noon.

In a word, Natsagdorj et al. (2003), indicate that mean duration of dust storms in Mongolia correlate well the frequencies of dust storms occurrence. The same is true in China.

4. Dust storm events changes in various regions

4.1. The stages of dust storm events in each region and their interannual changes

The 47-year changes of various dust storm events in each region were statistically analyzed according to the seven regional divisions of dust storms above. The regional mean results showed that the maximum of the mean annual occurrence days of dust storms was 13.6 days in South Xinjiang Region, the second was 12.8 days in Hexi Region, and the minimum was 1.6 days in Northeastern China Region. The maximum of the mean annual occurrence days of blowing dust was 47.1 days in Hexi Region, the second was 41.4 days in South Xinjiang Region, and the minimum was 5.1 days in North Xinjiang Region. The maximum of the mean annual occurrence days of floating dust was 94.4 days in South Xinjiang Region, the second was 21 days in Hexi Region, and the minimum was 1.3 days in North Xinjiang Region.

The statistical results concerning the occurrence days of various dust storm events from 1954 to 2000 in each region were as follows: The maximum of 47-year mean descending rate of dust storm was 0.53 days per year in the Qinghai-Xizang Region and the second was 0.42 days per year in South Xinjiang Region. The maximum of 47-year mean descending rate of blowing dust was 0.67 days per year in the Qaidam Basin Region and the second was 0.62 days per year in South Xinjiang Region. The maximum of 47-year mean descending rate of floating dust was 0.85 days per year in Hexi Region and the second was 0.66 days per year in the Qaidam Basin Region.

In order to contrast directly the differences among various dust storms in different regions, the South Xinjiang Region, Hexi Region, Qaidam basin Region and Northeastern China Region were chosen as four representative regions, and the curves of interannual variation of mean annual occurrence days of various dust storm events in the four regions were drawn (Fig. 6). Fig. 6a shows that, in general, mean annual occurrence days of dust storms monotonously decrease with fluctuation in the four regions from 1954 to 2000. Among them, the maximum number of annual occurrence days of dust storms occurred in the mid-1950s. After that they began to decrease, and decreased quickly in South Xinjiang Region and Hexi Region especially from the mid-1970s to the mid-1990s. They decreased to the minimum in 1997. Since 1998 they have been increasing. Figs. 6b and c show that the interannual variations of regional mean annual occurrence days of blowing dust and floating dust are different slightly from that of the dust storm. They increased with fluctuation from the mid-1950s to the mid-1970s and reached their peaks in the mid-1970s, then decreased until 1997. The annual occurrence days of blowing dust in the four regions have been increasing again since 1998, but those of floating dust do not evidently reveal this phenomenon.

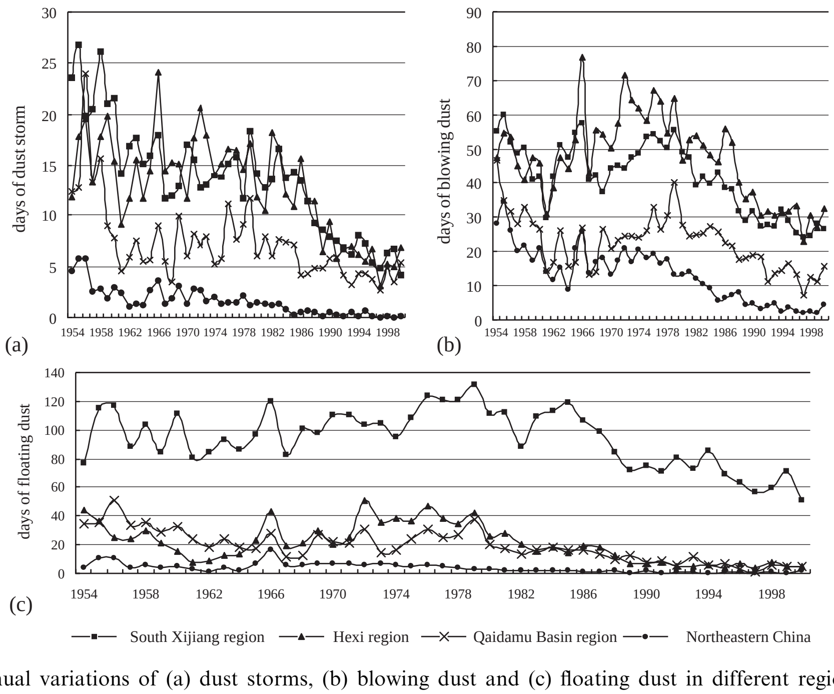

Fig. 6. The interannual variations of (a) dust storms, (b) blowing dust and (c) floating dust in different regions of China during 1954–2000.

Table 6
Variance of occurrence days of dust storms, blowing dust and floating dust in different regions of China

Type	North Xinjing	South Xinjiang	Hexi	Hetao	Qaidam	Qinghai-Xizang	Northeastern China
Dust storm	0.04	0.84	0.68	0.25	0.41	0.73	0.05
Blowing dust	0.03	0.36	0.55	0.36	0.22	0.25	0.22
Floating dust	0.001	0.38	0.17	0.08	0.11	0.002	0.01

Table 7
The percentage of 47-year mean occurrence days of dust storms in every month in different regions in China

Region	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
North Xinjiang	0.34	0.89	2.80	18.57	18.46	13.53	12.19	10.17	10.30	8.72	2.01	2.01
South Xinjiang	1.14	3.39	10.74	19.19	20.47	16.69	12.04	8.04	4.14	1.96	1.34	0.86
Hexi	3.38	5.38	12.90	20.70	17.84	12.16	9.86	6.17	2.84	2.37	3.35	3.06
Hetao	4.96	7.61	14.83	30.95	18.89	8.35	3.13	1.09	0.95	1.28	3.19	4.78
Qaidam	4.63	11.56	18.61	20.26	15.20	9.07	5.80	3.93	2.06	2.09	3.23	3.56
Qinghai-Xizang	17.04	20.12	18.79	13.04	6.84	1.90	0.77	0.45	0.45	1.09	7.09	12.43
Northeastern China	6.43	5.85	14.99	33.86	20.53	9.67	3.50	0.68	0.78	0.31	1.41	1.99

Table 8
The percentage of 47-year mean occurrence days of blowing dust in every month in different regions in China

Region	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
North Xinjiang	0.48	0.62	2.14	16.77	17.74	14.87	12.91	12.39	9.77	8.73	2.42	1.17
South Xinjiang	1.86	3.99	10.83	15.62	17.15	15.69	12.39	9.22	6.35	3.52	1.95	1.43
Hexi	4.70	6.44	12.51	17.02	15.48	10.59	8.94	7.11	4.20	4.01	4.62	4.38
Hetao	6.37	7.78	14.19	22.53	17.38	8.87	4.17	2.28	1.81	3.03	5.48	6.12
Qaidam	4.77	10.41	18.05	19.22	14.84	8.69	6.56	4.84	2.96	2.80	3.36	3.50
Qinghai-Xizang	15.68	18.95	17.70	13.57	8.08	1.90	0.77	0.47	0.71	2.23	8.21	11.72
Northeastern China	7.88	8.47	15.72	26.03	19.41	7.42	1.98	0.73	1.25	2.91	3.61	4.61

Table 6 shows that the maximum variances of occurrence days of both dust storm and floating dust existed in South Xinjiang Region, while that of blowing dust existed in the Hexi Region. These were consistent with the distributions of their 47-year mean maximum occurrence days and indicate that the maximum inter-annual variety of dust storm events happened in their source areas. Furthermore, Table 6 also shows that, of the three kinds of dust storm events, both interannual variety of dust storms in the same region (except Hetao and Northeast China regions) and their differences among each region were all of maximum value. This indicated that the effects of climatic factors and surface conditions on a dust storm's occurrence were primary, on blowing dust were secondary, and on floating dust were tertiary.

4.2. Annual variations of dust storm events in each region

The percentages of 47-year mean occurrence days of dust storm, blowing dust and floating dust in each region in every month in China are given by Tables 7–9. It has been shown that the maximum percentages of 47-year mean occurrence days of dust storm events occur usually in April in most parts of China. But in the Qinghai-Xizang Region, the highest frequency of dust storm and blowing dust occurrence appeared in February and that of floating dust appeared in March. The month in which blowing dust occurrence had the highest frequency was May in the whole Xinjiang Region. But, the highest frequency of dust storm in the South Xinjiang Region was in May.

The statistical results in Tables 7–9 also indicate that, of the seven different sub-regions, both Hetao Region and Northeastern China Region were obviously affected by monsoon climate. The months in which dust storm events occurred frequently were relatively centralized and mainly concentrated in the spring months of March, April and May. The occurrence days of dust storm events in the spring amounted to 60–70% of the whole year. However, in the Xinjiang Region, which was less affected by monsoon climate, the months in which dust

Table 9
The percentage of 47-year mean occurrence days of floating dust in every month in different regions in China

Region	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
North Xinjiang	2.63	3.74	10.94	30.19	17.87	6.51	6.09	4.43	6.65	6.23	2.08	2.63
South Xinjiang	2.78	6.28	13.79	14.61	13.31	10.23	9.56	8.94	7.92	5.70	4.07	2.80
Hexi	5.85	7.92	16.88	18.86	14.81	8.49	5.98	4.79	3.17	3.57	4.58	5.09
Hetao	7.48	8.73	17.80	24.10	15.97	6.41	2.36	1.71	1.20	2.55	5.44	6.25
Qaidam	4.43	8.76	19.73	21.82	16.46	7.83	5.64	4.46	2.30	2.28	2.89	3.41
Qinghai-Xizang	9.95	19.13	23.95	21.15	9.33	2.95	0.31	0.31	0.83	0.10	2.49	9.49
Northeastern China	7.93	9.47	16.67	31.08	16.43	3.29	0.33	0.22	0.97	1.76	5.56	6.30

storm events occurred frequently were relatively decentralized. In spring, this seasonal occurrence days of dust storm events amounted to 50% of the whole year, while in summer the dust storm events occurred sometimes. In the remaining three regions the high frequency months of dust storm events were basically concentrated in spring, up to about 50–60% of the whole year.

5. Conclusions and discussions

In this paper, three main conclusions can be drawn as follows:

(1) In China, there are two regions where dust storm events occur frequently: one center around Minfeng and Hetian in the South Xinjiang Basin, while the other center around Minqin and Jilantai in the Hexi Region. In the South Xinjiang region, the maximum of 47-year mean annual occurrence days of dust storms was 35.8 days, blowing dust 81.1 days, and floating dust 208 days; and in the center of Hexi region, maximums were 28.1 days, 96.2 days and 70 days, respectively. Furthermore, the spatial distributions of the various types of dust storm events were different. The dust storms mainly occurred in the arid and semiarid areas covered with the deserts and desertification lands in Northern China. The blowing dust and floating dust not only occurred in the same areas where dust storms occurred, but also in neighboring areas. The range of blowing dust extended northeastward and southeastward. But floating dust mainly extended southeastward to the low-latitude regions such as the East China Plain and the area of the middle and lower reaches of the Yangtze River. Compared with blowing dust, the floating dust very seldom occurred in the high-latitude areas such as North Xinjiang and Northeast China.

(2) The frequencies of dust storm events in China decreased during 1954–2000. They were the highest in the middle 1950s and the lowest in 1990s. However it has gradually increased since 1998. In China, the interdecadal change of dust storm events shows a short period of 3–4 years and a long period of 11–12 years. Dust storm and blowing dust most frequently occurred in spring (respectively 55% and 50% of the whole year). The daily variation of the dust storm events is also remarkable. Most of dust storms happened in the afternoon, 64.55% (42.2%) of them occurred during 12:01–21:00 LST in Minqin (Minfeng). About 30% dust storms occurred between 18:01–21:00 LST, after which time the frequency of dust storms decreased quickly. This phenomenon shows that thermal instable condition plays an important role in the formation of dust storm. In addition, the duration of dust storms occurring in Minfeng of the South Xinjiang region is longer than that in Minqin of the Hexi region in general.

(3) The areas subject to dust storms can be divided into seven sub-regions by cluster analysis with reference to the division of arid climate in China. These are the North Xinjiang Region, South Xinjiang Region, Hexi Region, Qaidam Basin Region, Hetao Region, Northeastern China Region and Qinghai-Xizang Region. The dust storms and floating dust occur with the highest frequency in the South Xinjiang Region, while blowing dust occurs with the highest frequency in the Hexi Region. The spatial averages of 47-year mean annual occurrence days in the three areas were 13.6 days, 94.4 days, and 47.1 days, respectively. The occurrence days of dust storm events decreased generally in all seven regions from 1954 to 2000. The maximum descending rate and variance of dust storm events during this period were in the South Xinjiang Region and the Hexi Region.

In addition, two problems about dust storm events in China are especially worth studying. The first is that although the occurrence days of dust storms and floating dust were more in South Xinjiang region than in Hexi region, the annual occurrence days of blowing dust and its variance were more in Hexi region than in South Xinjiang region. May be there are some other influencing factors besides the obvious occurrence of strong wind arising from special terrain in Hexi region. The second question well worth further examination is that although the dust storms and blowing dust often occurred in the high-latitude areas of North Xinjiang region, in southeastern Xizang plateau and in the

Northeastern China Region, why did floating dust very seldom occur there?

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