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Regional characteristics of dust storms in China

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Abstract

Regional characteristics of dust storms in northern China are analyzed using a rotated empirical orthogonal function (REOF), based on the annual days of dust storms from 1954 to 1998. The relationships between regional dust storms corresponding to other factors such as precipitation and temperature are explored.

The results show that five leading modes of dust storms exist in the following areas: the Taklamakan Desert (Tarim Basin) over the Xinjiang region (far northwestern China), the eastern part of Inner Mongolia (North China), the Tsaidam Basin, the Tibetan Plateau, and the upper reaches of the Yellow River (Gobi Desert). These areas are associated with an arid climate and frequent winds. For the first mode in the Tarim Basin, most dust storms appear in the 1980s, while dust storms become less frequent in the 1990s. The second mode (North China) shows the highest frequency of dust storms in the mid-1960s but the frequency decreases afterward. The third mode indicates a decreasing trend of annual dust storms after the mid-1960s but with a high interannual variability. The fourth mode also shows a decreasing trend but with a low interannual variability. The fifth mode displays a high frequency of dust storms in the 1970s followed by a decreasing trend.

For the five modes of dust storm distribution, four of the centers are located in desert regions. The annual dust storms of a selected station in each mode region are shown to compare the coefficient time series of these modes. The negative correlation between the prior winter temperature and dust storm frequency is identified for most stations. There is no consistency in the correlation between the dust storm frequency and the annual rainfall as well as the prior winter rainfall at these stations. The activity of dust storms in northern China are directly linked to the cyclone activity, especially for the interdecadal variability.

Keywords: Dust storms; Regional characteristics; China; Rotated empirical orthogonal function

1. Introduction

As pointed out by Goudie and Middleton (1992), dust storms have caused serious environmental consequences and hazards to human activities in different parts of the world. China is located in the East Asian monsoon region, where arid and semiarid climates dominate in the northern parts of the country. In this region, the monsoon can cause not only drought/flood and cold/warm events, but also windy conditions and air pollution (Xu, 2001; Jie, 1999; Goudie, 1983). The dust storm records in Chinese literature have been referred to as "yellow wind", or "black wind" (Qian et al., 1997; Wang et al., 1997; Zhang, 1997), as well as "dust rain" or "dust fog". The phenomena usually occur in the spring and early summer months (Qian, 1991). The earliest known record of dust rain occurred in 1150 BC, as found in a historical book (after Liu et al., 1981).

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Zhang (1984) used 1156 historical records to show the decadal frequency of dust rain years in China since AD 300. In the 1970s, several studies were conducted to understand the dust storms in northern China, such as in Gansu Province (Xu et al., 1979). On 5 May 1993, a very strong dust storm (known as "5 May black wind") occurred in northwestern China and caused huge damage to human life and property. During the period 1995–96, the Chinese government supported a project to investigate dust storms in northwestern China. A book entitled *Study on the Duststorm in China* was published by China Meteorological Press (Fang et al., 1997). In this book, a wide range of topics including the climatic characteristics, forecasting, remote monitoring, transport, deposition, numerical simulation, and service management of dust storms were discussed. However, all of the studies were limited to case analyses. A systematic study of dust storms in China for a whole is still unseen and the long-term trend is unknown. The reason for this is that the records of dust storms are individually stored at local stations and there is no statewide database of dust storms (Xu and Hu, 1997).

In our previous work, the interannual variability and long-term trend among dust storm frequency, dust weather (including dust storms, dust haze, and blowing dust) frequency, air temperature, and cyclone frequency in northern China were investigated using homogenous data sets for several decades (Qian et al., 2002). It was found that the number of dust storms and dust weather that occurred in the 1950s–1970s nearly doubled after the mid-1980s in northern China. The reason for this is that the warming in Mongolia and cooling in southern China reduced the meridional temperature gradient, resulting in a reduced cyclone frequency in northern China. The preceding winter temperature and spring cyclone number were used to construct a dust storm index in eastern China. In the Tarim Basin, the high frequency of dust storms has been attributed to decreased precipitation and to the arid-hot climate.

Geologically, several desert basins are situated in northern China: the Xinjiang region in far northwest China, the upper Yellow River valley in northwest China, and the eastern part of Inner Mongolia in northern North China (Fig. 1). These deserts are the Taklamakan Desert and the Tsaidam Basin in the Xinjiang region, the Gobi Deserts in the west of the upper Yellow River valley, the middle Yellow River valley, and northern North China. The climatic conditions such as precipitation, air temperature, and wind (cyclone activity) may be mostly linked to the frequency of dust storms. The regional features of dust storms in various areas over northern China can be related to these factors with different levels of significance. These regional features and relations were not investigated in detail in our previous paper (Qian et al., 2002). This paper will focus on the regional characteristics of dust storms and their relationships with other factors. After the introduction, a description of the data sets used in the study is given in Section 2. A rotated empirical orthogonal function (REOF) is introduced in Section 3. The temporal–spatial distributions of dust storms derived from the REOF analysis of the dust storm data for 1954–1998 are given in Section 4. The climate and dynamical control factors in the formation of dust storms are discussed in Sections 5 and 6. Finally, a discussion and summary are given in Section 7.

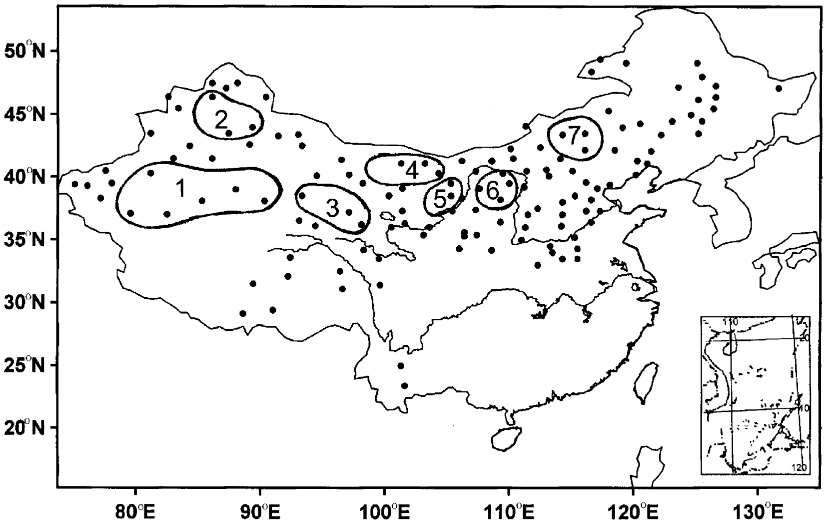

Fig. 1. Locations of 135 stations in which dust storms were observed. The numerals mark major deserts: (1) for the Taklamakan desert in the southern Xinjiang region, (2) for the northern Xinjiang region, (3) for the Tsaidam Basin, (4) and (5) for the Gobi Desert in the west of the upper Yellow River valley, (6) for the Ordos Desert in the middle Yellow River valley, and (7) for northern north China.

2. Data description

In this paper, four data sets are used. The first data set contains the dust events observed from stations. The data set of daily dust storms was obtained from the China Meteorological Administration. Using the data set of dust events from 338 stations for 1954–1998, the yearly mean distribution of dust storms was shown in our previous work (Qian et al., 2002). The areas above one day of dust storm event per year cover northwest China and northern China except Heilongjiang Province in northeast China. The high-frequency center with more than 30 days of yearly dust storms is found in the Tarim Basin (Taklimakan Desert) region. Another center with yearly dust storms of more than 15–20 days is situated in the central western Inner-Mongolia region. According to this coverage, we select the observed daily dust storms from 135 stations only covering northern China (Fig. 1). Based on the standards of surface meteorological observation (Central Meteorological Bureau, 1979), dust storms are the result of strong turbulent wind systems entraining particles of dust into the air, reducing the visibility to 1000 meters and below. The standard of dust storms in China is the same as described by Goudie and Middleton (1992). In China, four types of dust events including dust storms, dust haze (horizontal visibility reduced to $<10\,000$ m), blowing dust (visibility reduced to 1000–10 000 m), and dust devils are usually considered in the daily observation.

The days of dust storm events were divided according to a daily interval of 24 h from 20:00 (Beijing local time BLT). If a dust storm event lasts past 20:00 BLT, two days are counted. On the other hand, if there are several events of dust storm in a day, it is marked as 1 day only. We generated statistics of hourly dust storms at the Beijing station. The results show that the increase of dust storms starts from 09:00 BLT and a decrease begins rapidly after 20:00 BLT. The peak time is at 17:00 BLT with about 9% of daily dust storms while the percentage reduces 1% at 8:00 BLT and 09:00 BLT. For two periods, 09:00–20:00 BLT and 21:00–08:00 BLT, the ratio of dust storms is 4.53:1, meaning that more dust storms were observed during the daytime and fewer were observed during the nighttime. The reason may be due to the difference in wind speed and thermal convection near the surface during the day and at night. Therefore, this division at 20:00 BLT should not have a large impact on the calculations. In the following description, we use the term “dust storm frequency,” which means the number of dust storm days that happened in 1 year. Finally, a data set of yearly dust storm days from 135 stations for 1954–98 was formed.

The second and the third data sets contain monthly air temperature and precipitation, respectively, from 160 stations obtained from the China Meteorological Administration for 1950–98. The fourth data set contains the cyclone frequency (Qian et al., 2002) derived from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis of 850-hPa geopotential height (gph) with a horizontal resolution of 2.5 latitude by 2.5 longitude.

Among the above four data sets, only those of temperature and precipitation are from the same stations while the other data sets are from different stations or grids. To discuss the relationship of dust storms with precipitation and temperature, only several stations are selected. To show the influence of cyclone activity, tracks of the cyclone movement are plotted and discussed.

3. Method description

In China, dust storms are mainly concentrated in the northern part of the country. Over this area, there are several centers of dust storm formation. These centers may be linked with local conditions such as deserts and climatic environments. To pinpoint these centers of dust storm activity, an optimal mathematical method that can obtain the basic features of a variable is needed.

Empirical orthogonal function (EOF) analysis was introduced to the atmospheric sciences by several pioneers (e.g., Lorenz, 1956). EOF analysis provides a convenient mathematical method for studying the spatial and temporal variability of a variable. In the last two decades, EOF analysis has become a very popular diagnostic tool, and has been widely used in the study of climatology and oceanography (Saji et al., 1999; Behera and Yamagata, 2001).

Previous works have applied EOF analysis to highlight potential physical mechanisms associated with climate variability (Saji et al., 1999). Recently, Dommenget and Latif (2002) indicated that caution should be used when trying to interpret these statistically derived modes and their significance. To simplify the physical mechanisms underlying the characteristic patterns, or to seek “physical” modes, which have some good properties such as “simple structure”, real physical background, and so on, the rotated EOF (hereafter REOF) approach was described by Richman (1986). REOF supplies a new set of modes by rotating the vector space of the initial EOFs and improves the physical interpretation of the original field. It has received more attention and has also been widely used in meteorological and climatic studies in recent years (e.g., Kelly and Jones, 1999; Mestas, 2000).

In this paper, we use REOF analysis to study the yearly dust storm days in northern China for 1954–1998. The purpose is to reveal the physical interpretation of dust storms in China. From Fig. 1, the stations are homogeneously scattered in northern China and cover major desert regions.

Dust storms are not only observed in areas of the original dust sources, but the dust is also transported to other places by wind or weather systems such as cyclone activity. To explain the features revealed by REOF analysis of the dust storm days in northern China, cyclone-wave activity and their tracks need to be calculated first.

In this study, we first determine the location of a wave cyclone as a low center that is counted at each grid point per day. The following analysis procedures have been taken into account.

(i) The critical value of 1400 gpm at the 850-hPa level is used to define total waves aloft.
(ii) The value of the grid point that determines the central location of a wave aloft must be lower than that of the surrounding points.
(iii) The value of the central location is set to the meridional and zonal arithmetic mean of all points if these points have the same values.

The criterion of 1400 gpm has been taken after carefully examining many weather maps. It is also consistent with the experience of synoptic analysis in China. Cyclones in East Asia for the spring season can be identified based on this criterion.

After we obtain the daily cyclone locations, a track of a single cyclone can be determined by the sequence of daily positions. A seasonal cyclone track at a grid point is closely related to two factors. One is the maximum frequency of cyclone motion directions and the other is the average speed of cyclone movement at the maximum direction. The frequency of cyclones can also be identified from the density of these tracks.

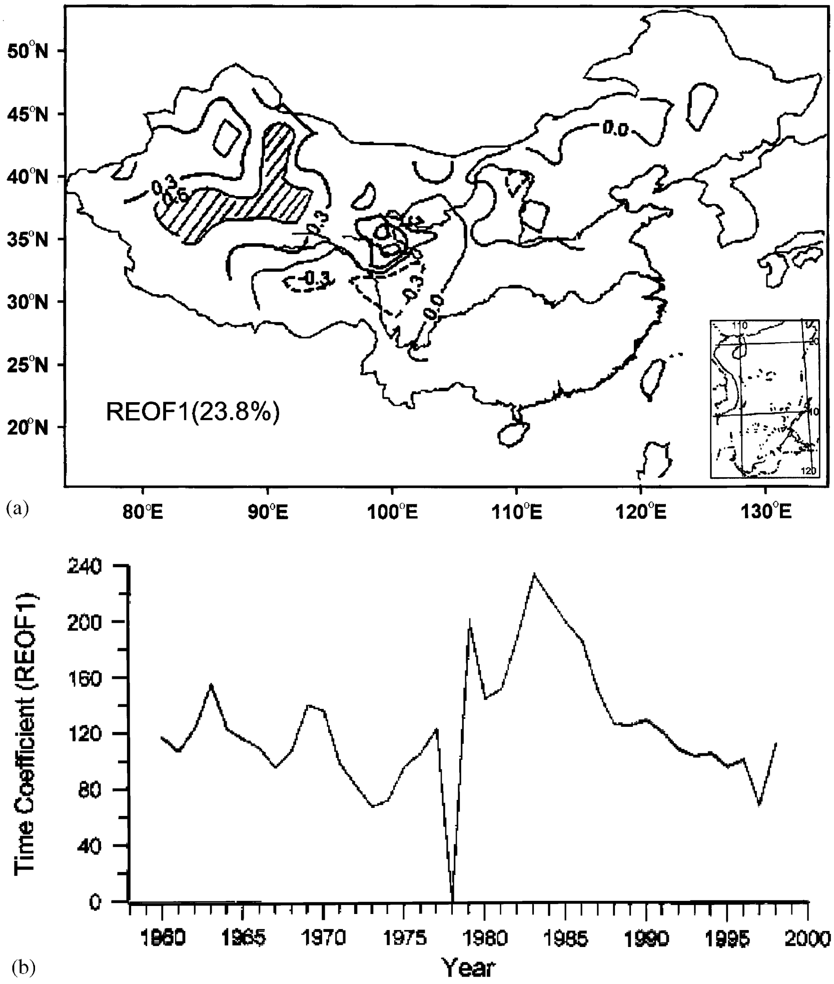

Fig. 2. (a) The first mode (REOF1) of dust storms with about 24% of the total variance and (b) its coefficient series from 1960 to 1998. Shaded areas indicate the value more than 0.6 and dashed lines indicate the value <0.0.

4. Temporal–spatial features

Based on the dust storms at 135 stations for 1954–98, the first five REOF modes of dust storms and their coefficient time series in northern China are shown in Figs. 2–6. The first five modes explain approximately 99% of the total variance of dust storms. We first explain what the coefficient means and from what function the coefficient is derived. REOF or EOF analysis provides a convenient method for studying spatial and temporal variability. Because this method splits the spatial–temporal field such as dust storm frequency into a set of orthogonal modes, it is a powerful approach to analyze the characteristics of the spatial patterns and their temporal variations, which exist in the original field. If the modes are ordered or localized, each successive mode explains the maximum possible amount of the remaining variance in the original field. The coefficient time series of each mode can represent an observed time series averaged near the mode's center. The mode's center (anomalous center relative to the original field) becomes stronger if the coefficient value is larger, and it does not exist if the coefficient value is near zero.

In China, the largest desert is located in the southern Xinjiang region over the Tarim Basin. Fig. 2a shows the first mode of dust storms from the REOF method. The mode covers the Tarim Basin in the southern Xinjiang region and other places in the northern Xinjiang region. The first mode in the Xinjiang region accounts for about 24% of the total variance. In our previous work (Qian et al., 2002), the high-frequency center with yearly dust storm days of >30 was found in the Tarim Basin (Taklimakan Desert) region. The time coefficient series for the first mode is plotted in Fig. 2b, indicating that more dust storms appeared in the 1980s than in other decades for the region. The year with the lowest frequency of dust storms was 1978 and the year with the highest was 1983.

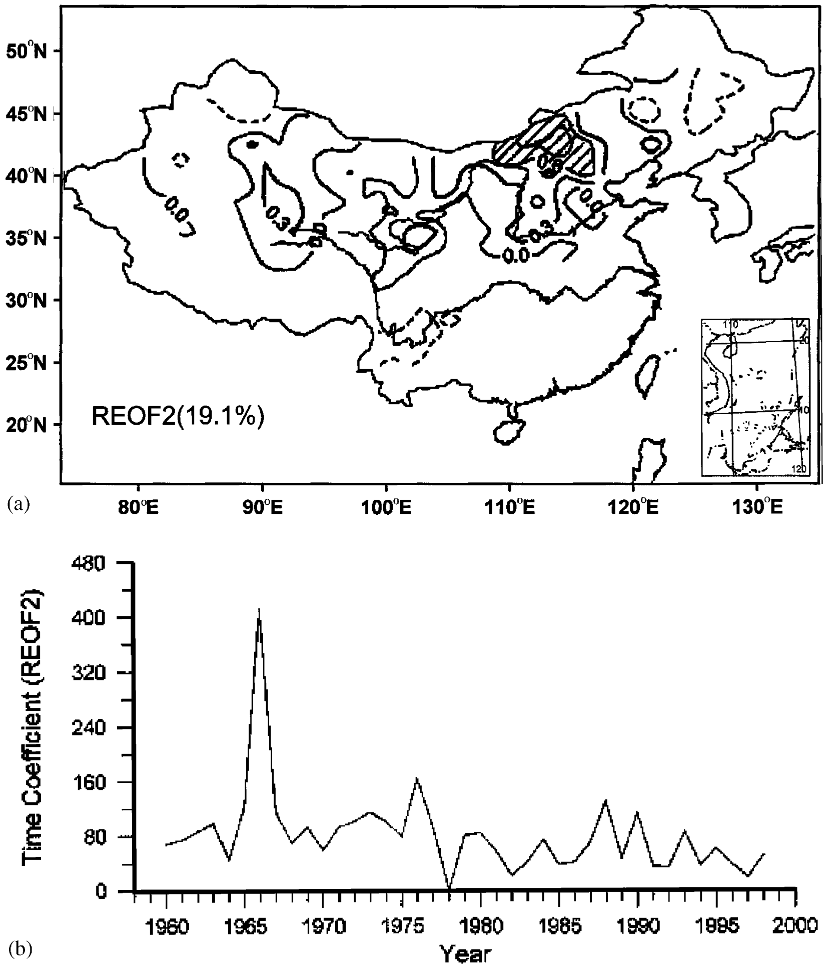

Fig. 3. Same as in Fig. 2 except for the second mode (REOF2) with about 19% of the total variance.

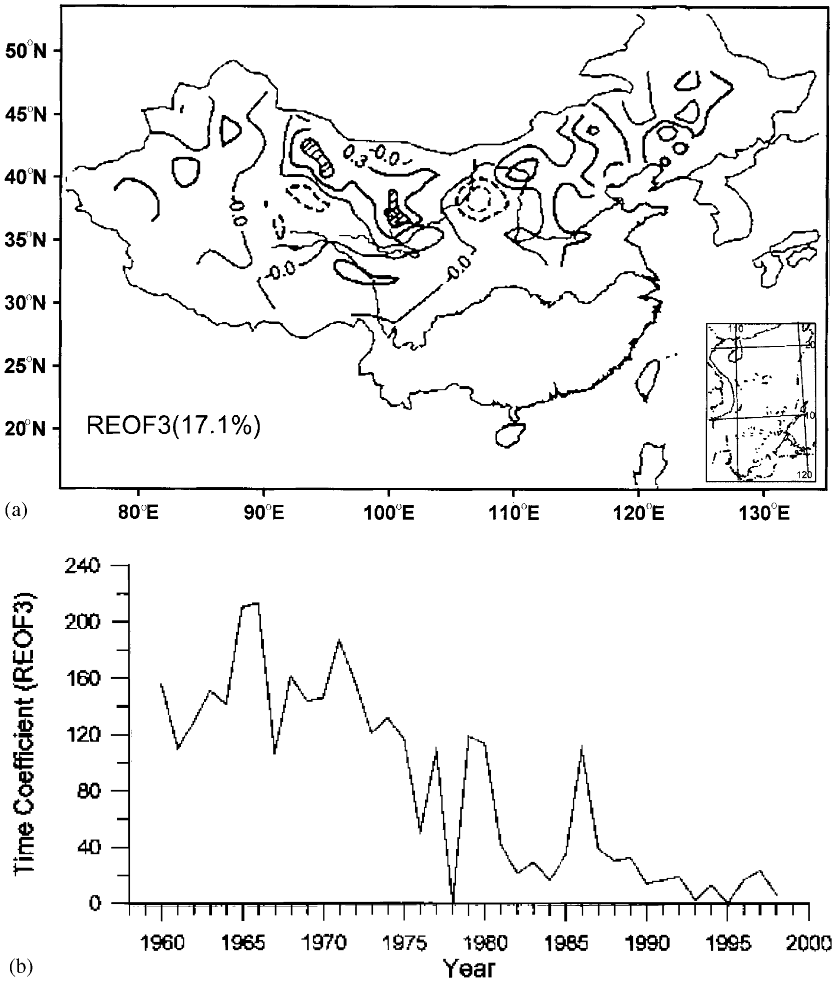

Fig. 4. Same as in Fig. 2 except for the third mode (REOF3) with about 17% of the total variance.

The second mode (19% of the total variance) shows a center in northern North China (Fig. 3a), where a desert is situated in the eastern part of Inner Mongolia. This mode with a high coefficient (0.3–0.6) covers the entire North China region including Beijing. Its time series is shown in Fig. 3b, indicating the highest frequency of dust storms in 1966.

The third mode shows 17% of the total variance with the center in northwest China (Fig. 4a). This area is near the desert of the Tsaidam Basin. The time series (Fig. 4b) with a decreasing trend but with significant interannual variability is different from the first two modes' series. It is noted that the highest frequency of dust storms occurred in 1965 and 1966. In the last decade, the frequency of dust storms becomes rather low.

The fourth mode (15% of the total variance) with the positive mode coefficient (0.3–0.6) is mainly situated in the Tibetan Plateau (Fig. 5a), where there is no desert region but typically high wind speed. A decreasing trend of the time series is noted in Fig. 5b. The highest frequency of dust storms in the plateau was in 1960. Another center of positive mode coefficients dominates in the middle Yellow River valley, which is influenced by the nearby desert.

The fifth mode (15% of the total variance) with a high coefficient (0.3–0.6) is located in the upper valley of the Yellow River (Fig. 6a) where the Gobi Desert is located. The REOF time series shows a high frequency in the 1970s (Fig. 6b). After the late 1970s, the frequency decreases.

In the above discussions, we have addressed the different features of distributions and variations of the dust storms that have been identified in different regions. The spatial patterns of dust storms are connected with the distributions of the deserts in China. The temporal evolutions of dust storms show a

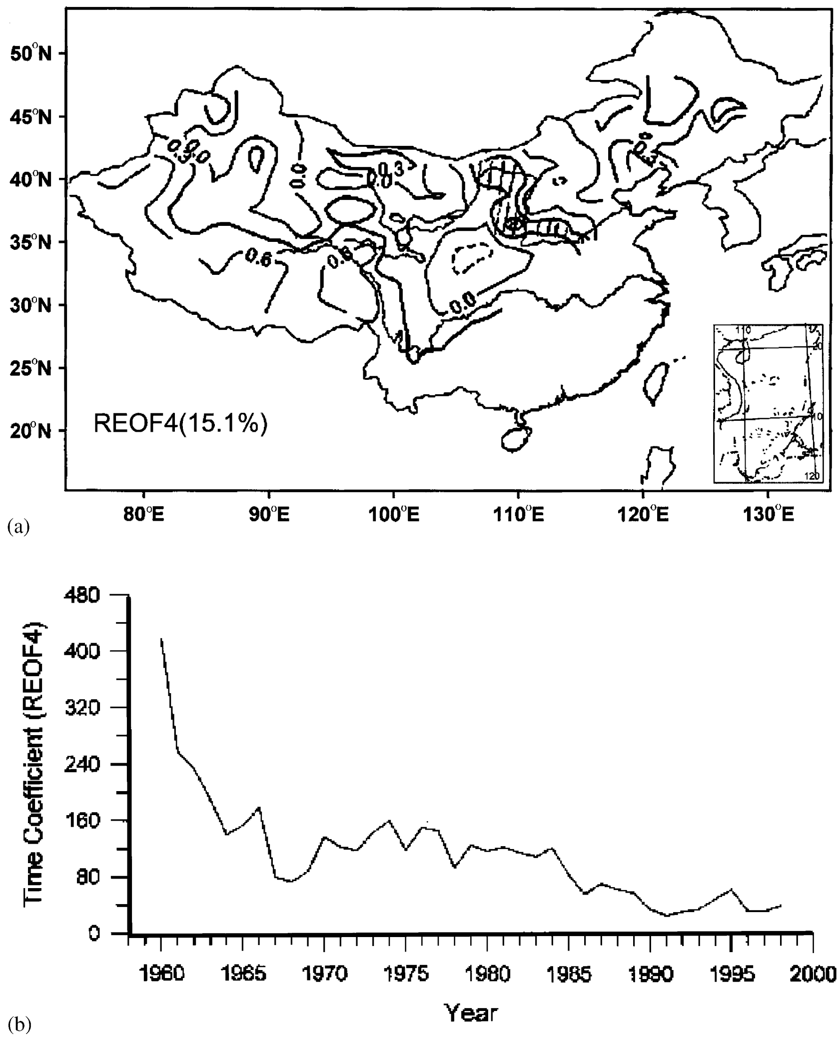

Fig. 5. Same as in Fig. 2 except for the fourth mode (REOF4) with about 15% of the total variance.

decreasing trend in the last decade but the highest frequency occurs during different periods and in different regions.

5. Climatic control

A dry climate should be one of important factors in forming dust storms. In this section, we choose some stations, which are located in the various mode domains, based on the REOF method. Fig. 7a displays three variables at the Qieme station (85°33′E, 38°09′N) in the center of the Tarim Basin. At this station, the annual frequency of dust storms reached 50 days in 1954 and 1955 then decreased to about 20 days per year in the 1960s and the 1970s. The second highest frequency of dust storms appeared in 1983 with a value of about 30 days. After 1985, the frequency of dust storms at this station decreases. In the 1990s, the frequency of dust storms was about 10 days per year.

At this station, the annual precipitation exhibits an increasing trend. The maximum annual precipitation was observed in 1991 with an annual value of about 130 mm. The highest frequency of dust storms was observed in the 1950s, which is consistent with the period of lowered annual precipitation. In the middle and late 1960s, the annual precipitation reached the second highest value and the dust storm days decreased. In the late 1980s, the annual precipitation was low and the dust storm days increased. The increased precipitation in the early 1990s is a major factor in reducing dust storm days at this station. The correlation between the annual precipitation and dust storm days at the station is calculated to have a value of −0.4 with the 99% significance level, indicating a negative relation.

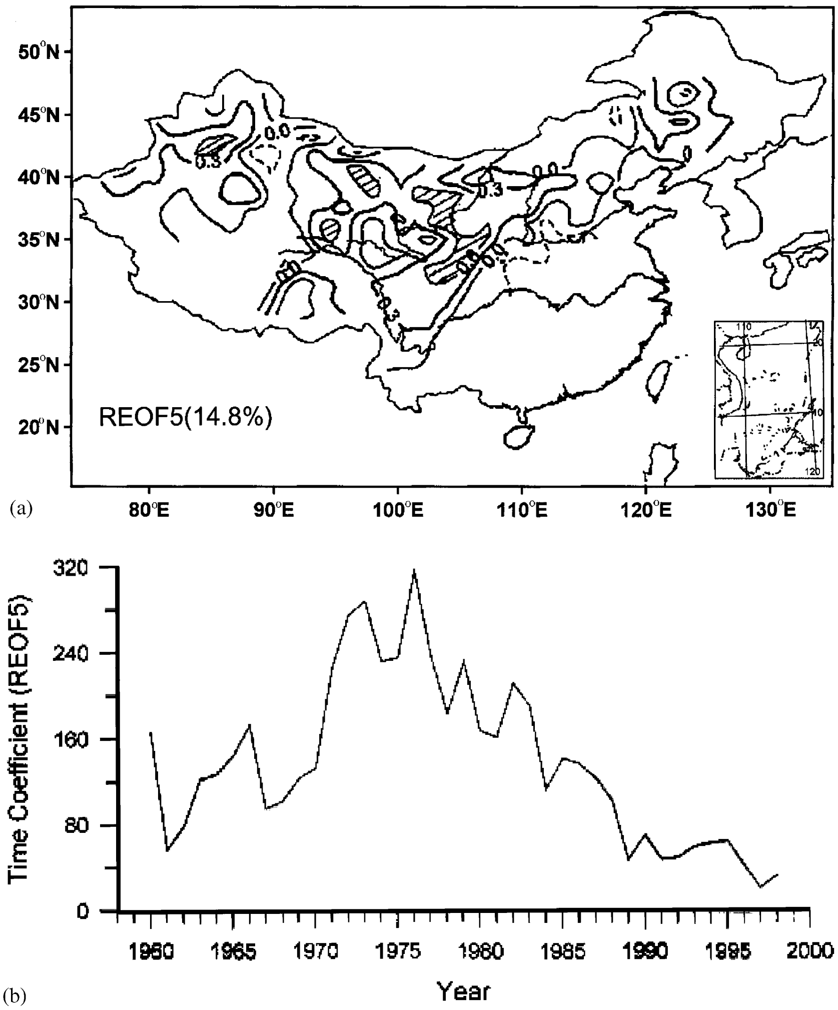

Fig. 6. Same as in Fig. 2 except for the fifth mode (REOF5) with about 15% of the total variance.

A negative correlation with a value of −0.25 between the air temperature in winter and the dust storms is noted at the station. It has been indicated that lower air temperature in the prior winter and high frequency of cyclones in spring contribute to dust weather and dust storm conditions (Qian et al., 2002). The physical cause may be that if sandy soil is heavily frozen during lower winter temperatures, it becomes desiccated more easily after melting in spring.

Beijing (116°19′E, 39°57′N) is situated in the second REOF mode of the dust storms. The correlation between the annual precipitation and dust storms in Beijing show that there is little linkage (Fig. 7b). The prior winter temperature has a negative relation to the dust storms. Their correlation is −0.5 with the 99% significance level. In 1956, the winter temperature reached the lowest value and the dust storm days have a high value. The opposite oscillations in phases can be noted from the precipitation and dust storm days before the 1980s. A decreasing trend of dust storms and an increase in winter temperature have continued since the late 1960s.

At Xining station (101°45′E, 36°25′N), a decreasing trend and decadal change of dust storms can be noted from 1950s to 1970s. The annual frequency of dust storms in the mid-1950s and the early 1970s reached 15 days, but it decreased to <5 days in the late 1960s and the late 1970s. In the last two decades, the dust storms at Xining station were observed only on 1 day in 1992 and 1994, respectively. The temperature shows an increasing trend. The correlation between the dust storm series and temperature is −0.44. There is little correlation between the dust storm series and the precipitation at Xining station. The activity of dust storms at Xining station is basically consistent with the time series of mode 3 (Fig. 4b). The reduction of the cold air activity in winter and spring due to a weakening of the Siberian High (Qian et al., 2001) can explain the increased temperature

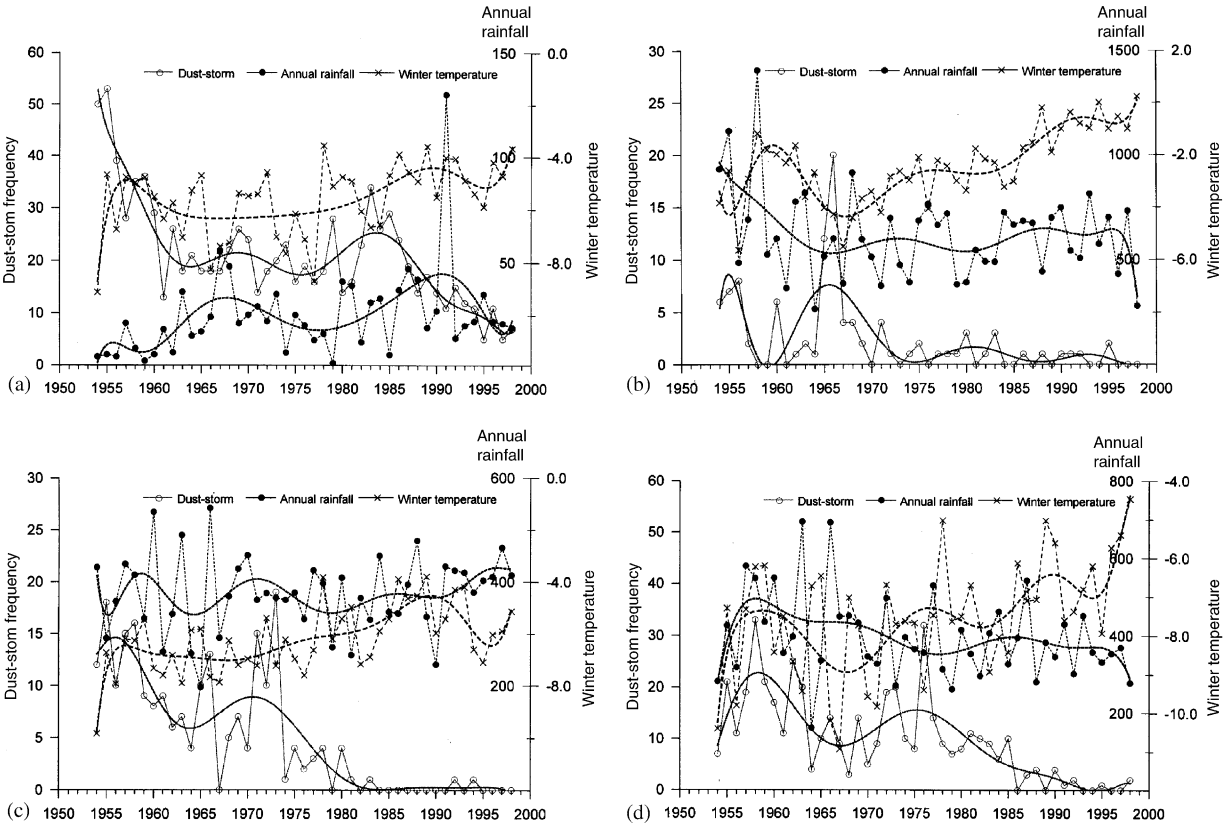

Fig. 7. Time series and their correlations of three variables (DS: dust storm, annual precipitation, winter temperature) at stations (a) Qieme (85°33′E, 38°09′N) in the center of the Tarim Basin, (b) Beijing (116°19′E, 39°57′N), (c) Xining (101°45′E, 36°25′N), and (d) Yulin (109°42′E, 38°14′N).

and reduced dust storm activity at Xining station after 1980s (Fig. 7c).

Fig. 7d shows the dust storm frequency as well as the annual rainfall and the prior winter temperature at Yulin station (109°42′E, 38°14′N) near the desert region in the middle Yellow River valley. A high frequency of dust storms occurred in the late 1950s and the middle 1970s. A decreasing trend of the dust storms was observed after 1980s. This variation of dust storm frequency is consistent with that of the time series of dust storm mode 5 (Fig. 6b). A decreasing trend of the annual rainfall and an increasing trend of the winter temperature at Yulin station were observed after the late 1960s. The correlation between the dust storm frequency and the temperature is −0.29. The correlation between the dust storm frequency and the annual rainfall is 0.37. This correlation of both dust storm frequency and annual rainfall at Yulin station is different from the other stations mentioned above. Yulin station is located near the desert. This positive correlation between dust storm frequency and annual rainfall needs to be investigated further.

In summary, we list the different correlations at various stations in Table 1. It can be identified that the negative correlation between dust storm frequency and prior winter temperature is commonly noted for these 10 stations. There is no consistency in the correlation between dust storm frequency and annual rainfall (or prior winter rainfall) at these stations. The negative correlation between dust storm frequency and annual (or prior winter) rainfall is found in the Tarim Basin in the Xinjiang region, while the positive correlation is noted at some local stations in the middle and lower Yellow River basin.

6. Dynamical control

Arid, semiarid, and desert regions provide a basic background for the formation of dust storms in China. The winter temperature is connected with the cold air activity in northern China (Qian et al., 2001). The frequency of dust storms in northern China is strongly related to the high frequency of cyclone activity in the

Table 1
Correlations between dust storm frequency (D) and parameters (annual and winter rainfall, R; and prior winter temperature, T) at various stations

Station	Regional no.	Longitude	Latitude	Corr(D&R)		Corr(D&T)	REOF mode
				Annual	Winter		
Hetian	51828	79°56′E	37°08′N	−0.10	−0.23	−0.10	1
Qieme	51855	85°33′E	38°09′N	−0.40	−0.16	−0.25	1
Beijing	54511	116°19′E	39°57′N	0.03	−0.01	−0.50	2
Zhangjikou	54401	114°53′E	40°47′N	0.21	0.16	−0.19	2
Xining	52866	101°45′E	36°25′N	0.05	−0.05	−0.44	3
Zhangye	52652	100°26′E	38°56′N	−0.04	0.00	−0.42	3
Yan’an	53845	109°30′E	36°36′N	0.02	0.20	−0.42	4
Yulin	53646	109°42′E	38°14′N	0.37	0.01	−0.29	4
Lanzhou	52889	103°53′E	36°03′N	0.04	0.18	−0.38	5
Yinchuan	53614	106°16′E	38°25′N	0.09	0.01	−0.24	5

Note: The significance level is 0.05 (95%) for the correlation coefficient 0.36, and 0.01 (99%) for the correlation coefficient 0.40.

spring season (Qian et al., 2002). As described in Section 4, the frequency distribution of dust storms in China has had a particular temporal–spatial evolution in the last four decades. Four modes of dust storms in northern China are directly linked to the desert regions. Dynamically, the domain of each mode may be concerned with the track of cyclone wave activity. Fig. 8 shows the averaged 850-hPa cyclone tracks in spring for 1948–1999. In the figure, the vector of the track indicates the direction of cyclone movement at the 850-hPa level climatologically in spring and the density of tracks shows more cyclone activity. According to this, four high-frequency regions of cyclone activity can be noted: the Tarim Basin, central northwest China, northern North China, and the upper Yangtze River valley. The dashed areas indicate the four regions of dust storm modes. In northern China, the high-frequency regions of cyclone activity are consistent with those of the dust storm modes. It is noted that in the Tarim Basin, the average cyclone finally converges in this mode region. In northwest China (near the Qinghai Lake), a cyclone track passes through two mode regions so that dust storms can influence many regions. In northern China, the second mode domain of dust storm is larger than that of the desert area. The track direction and the density can explain the extended area including Beijing.

Fig. 9 shows the cyclone tracks based on the cyclone activity in two periods, 1951–1970 and 1978–1997. It is noted that more cyclones can be found in the southern part of Mongolia near the China–Mongolia boundary for 1951–1970, compared to 1978–1997. We focus on the cyclone activity in the three regions. In the Tarim Basin (Fig. 9a), the cyclone frequency is high in the first period and some cyclones move out of the basin. In northwest China, the cyclones move southeastward and northeastward. In North China, some cyclones come from the northwest. A different feature is noted in the second period (Fig. 9b). In the Tarim Basin, cyclones are reduced and do not move out of the basin. There is no large change in the cyclone frequency in northwest China. In North China near Beijing, there are very few cyclones. These regional features of cyclone activity can explain why a decreased trend of dust storm frequency is experienced in North China while no significant change of dust storm frequency is experienced in northwestern China for the two periods. As we note from previous work (Qian et al., 2002), different relationships of dust storms in the Xinjiang region and eastern China have been identified. In the Xinjiang region, the dust storm frequency is strongly related to the local precipitation, while in eastern China the dust storms are dependent upon both temperature and cyclone activity.

7. Discussion and summary

From the above analysis, two time scales deserve attention in studying the variations of dust storm frequency, winter temperature, and cyclone activity. One is the interannual variability and the other is the interdecadal change. At the interannual timescale, 1978 is an anomalous year with the lowest dust series from modes 1, 2, and 3 (Figs. 2b, 3b and 4b), meaning that there are very few dust storms in that year. It was found that the winter temperature is the highest at the stations Qieme (Fig. 7a), Xining (Fig. 7c), and Yulin (Fig. 7d) in that year, relative to the period 1954–1998. There is also less cyclone activity in the spring of 1978 (figure omitted).

At the interdecadal timescale, dust storms, winter temperature, cyclone activity, and active centers of atmosphere experience changed abruptly in the late 1970s. This decadal change has been noted from other aspects such as sea surface temperature (Wang, 1995)

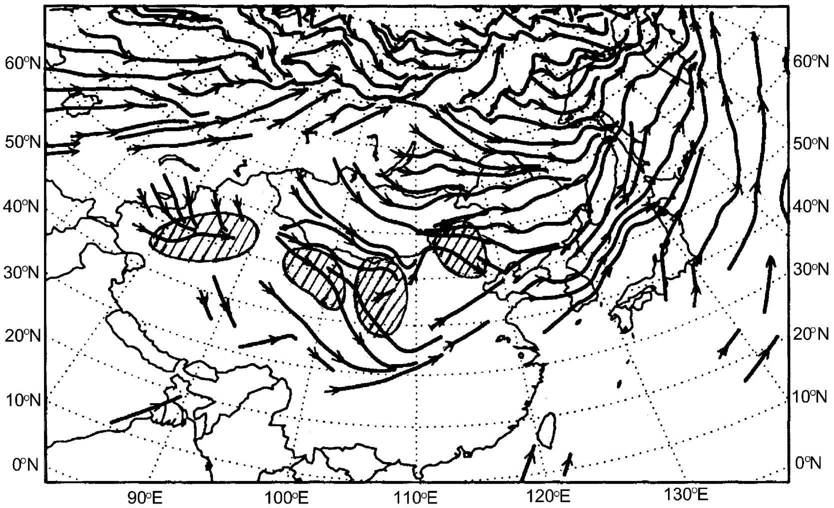

Fig. 8. The averaged 850-hPa cyclone tracks in spring for 1948–1999. The vector of the track indicates the direction of cyclone movement at the 850-hPa level, and the density of tracks indicates cyclone activity. The dashed areas indicate the four regions of dust storm modes.

and the subtropical high (Gong and Ho, 2002). During the winter season, the air temperature in northern China largely depends on the strength and location of the Siberian High (SH) and frontal cyclone activity. The strength of the SH weakens and its central position moves northwestward after 1980s (Qian et al., 2001). This leads to fewer and weaker frontal cyclones so that we can observe warmer winters and decreasing dust storm days in the last two decades in eastern China. The decadal change in cyclone activity can be noted obviously from their tracks (Fig. 9). Low-frequency climate phenomena such as the long-term SH change is a background for the high-frequency cyclone activity.

It was identified that the stronger SH in the winter and spring seasons will cause the frequent activity of frontal cyclone. The frontal cyclone activity in winter season will reduce winter temperature and it is useful to form dust storm sources. In the spring, the frontal cyclone activity is a dynamical condition of dust storm formation with frequent dry and cold air outbreaks.

Regional characteristics of dust storms in China, based on the annual days of dust storms from 1954 to 1998, are analyzed using the REOF method and are related to other meteorological factors by statistical methods. The new findings are highlighted as follows:

(i) Five leading centers of dust storms exist: in the Taklamakan Desert (Tarim Basin) over the Xinjiang region (far northwestern China), the eastern part of Inner Mongolia (North China), the Tsaidam Basin, the Tibetan Plateau, and the upper reaches of the Yellow River (Gobi Desert). These areas are characterized by low precipitation and frequent winds. For the first center in the Tarim Basin, the most dust storms appear in 1980s while the frequency of dust storms decline in 1990s. The second center (North China) shows the highest frequency of dust storms in the mid-1960s but the frequency declines after that. The third center indicates a reduced trend after the mid-1960s but has a high interannual variability. The fourth center also shows the reduced trend but with a low interannual variability. The fifth center displays a high frequency of dust storms in 1970s and then a reduced trend. For the five centers of dust storm distribution, four are located in desert regions.

(ii) The annual dust storm frequencies as well as the precipitation and temperature of a selected station in each mode region are shown to compare the time series of their REOF mode center. Examining the correlations among the annual dust storm frequency, the prior winter temperature, and the annual rainfall from 10 stations in the five REOF mode regions, various results are identified. A negative correlation between the dust storm frequency and the prior winter temperature is commonly noted at these 10 stations. There is no consistency in the correlation between the dust storm frequency and the annual (or prior winter) rainfall at these stations. A negative correlation between the dust storm frequency and the annual rainfall is found in the Tarim Basin over the Xinjiang region while a positive correlation is noted at some local stations over the middle and lower Yellow River basin.

(iii) Dynamically, the center of dust storms in northern China is linked to cyclone activity in density and

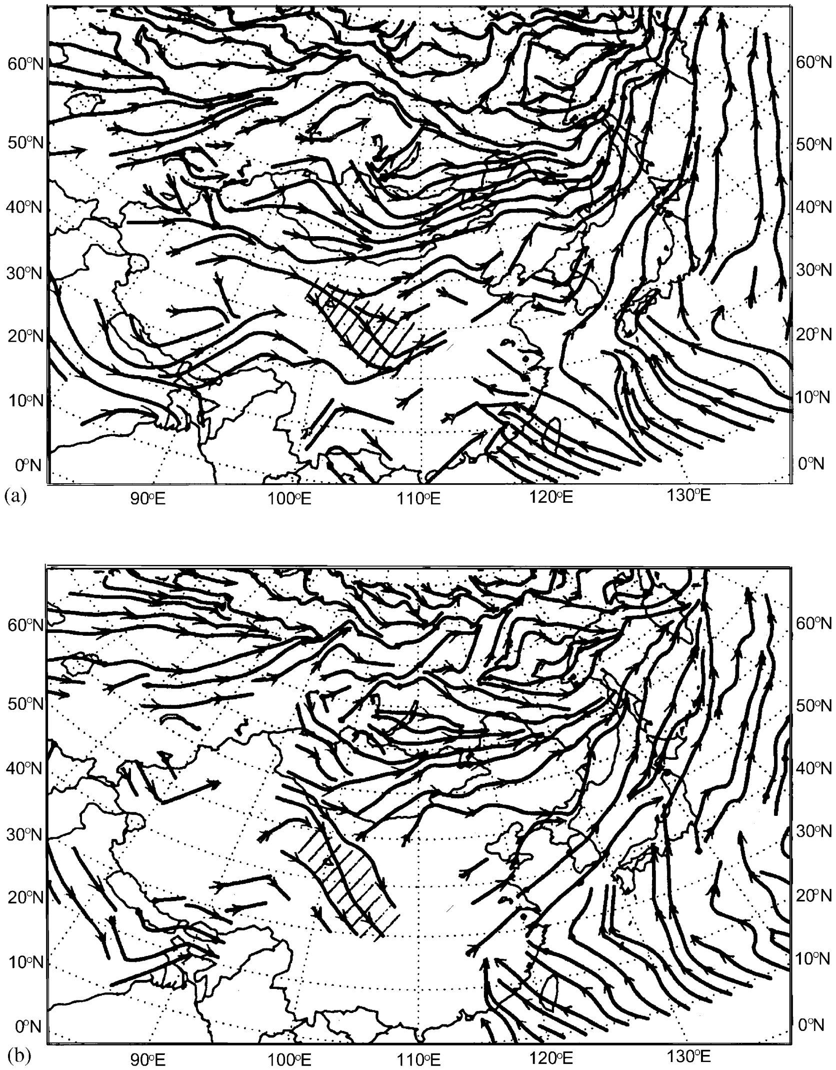

Fig. 9. Same as in Fig. 8 except for two periods (a) 1951–70 and (b) 1978–97.

track direction. Four high-frequency regions of cyclone activity are identified: the Tarim Basin, central northwestern China, northern North China, and the upper Yangtze River valley. Three are located in northern China and are linked to the dust storm activity. The interdecadal variability of the cyclone activity is obvious in the later decades. Its long-term trend and its local interdecadal changes may explain the variations of dust storm activity in China.

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