Variations of the Dust Storm in China and its Climatic Control

WEIHONG QIAN

Department of Atmospheric Sciences, Peking University, Beijing, China

LINGSHEN QUAN

CAAC Shandong Administration Bureau, Jinan, China

SHAOYIN SHI

Beijing Meteorological Bureau, Beijing, China

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ABSTRACT

In previous studies, limited meteorological observations were used to investigate the temporal–spatial changes of dust storms in China. Here, the authors use the daily 850-hPa geopotential height of NCEP–NCAR reanalysis for 1948–99 to examine the vortex fluctuations, which represent daily cyclone activity in east Asia. They also use the 1000-hPa air temperature data to explain the decadal change of the cyclone activity. In addition, the grid cyclone frequency for 1948–99 and the temperature and precipitation for 1950–98 are used to calculate the correlation with the dust weather frequency (for 1954–98) in China.

Results show that the interannual variability and long-term trend among dust storm frequency, dust weather frequency, air temperature, and cyclone frequency exist in northern China. In the eastern part of China, the frequencies of dust storms and dust weather in the 1950s–70s were about twice that after the mid-1980s. The reason for this feature may be due to the warming in Mongolia and cooling in northern China that reduced the meridional temperature gradient, resulting in the reduced cyclone frequency in northern China. In the Tarim Basin, the high-frequency dust storms have been attributed to less precipitation and to the arid-heating climate.

The frequency of dust storms (dust weather) is strongly related to the low air temperature in the prior winter season and the high-frequency cyclone activity in the spring season for most parts of eastern China. Based on this relationship, an index describing the dust weather (dust storm) frequency has been formulated. This index can well calibrate the variability of dust weather (dust storms) in northern China, except for the Xinjiang region in far northwest China.

1. Introduction

It is only in the last three decades that the dimension and relevance of the dust storm phenomenon in arid and semiarid areas has been realized. Environmental consequences range from excessive soil mass and nutrient loss in source areas to pedological effects in deposition area air pollution and meso- to macroscale climatic modification (Goudie 1983; Pye 1987; Littmann and Steinrucke 1989; Littmann 1991; Goudie and Middleton 1992). In the 1970s, it was identified that dust storms could affect the thermal balance of planetary radiation, resulting in climatic alteration (Idso 1974; Idso and Brazel 1977). Goudie and Middleton (1992) summarized some environmental consequences and hazards to human populations caused by dust storms in different regions of the world.

China is located in the east Asian monsoon region, where arid and semiarid climate dominates in the northern parts of the country. In this region, the strength of monsoon circulation can cause not only drought/flood and cold/warm events, but also windy conditions and air pollution. Some of the early records of dust storm activity in the world are recorded in ancient Chinese literature. They refer to dust falls in northern China 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 was in 1150 B.C., as found in a historical book (after Liu et al. 1981). Zhang (1984) used 1156 historical records to show the decadal frequency of dust rain years in China since A.D. 300. In the 1970s, some dust storm cases in northwest China, such as the Gansu Province (Xu et al. 1979), were investigated. In the 1980s, many cases of dust storms were reported in Chinese local bulletins, such as Xinjiang and

Corresponding author address: Dr. Weihong Qian, Department of Atmospheric Sciences, Peking University, Beijing 100871, China.
E-mail: qianwh@pku.edu.cn

Qinghai, in the northwestern provinces. On 5 May 1993, a very strong dust storm (or 5 May black wind) happened 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 the dust storms in northwestern China. Finally, a book titled *Study on the Dust Storm in China* was published by China Meteorological Press (Fang et al. 1997). In this book, a wide range of topics including the weather climate characteristics, forecasting, remote monitoring, transporting deposition, numerical simulation, and service management of dust storms were discussed. However, all of the discussions were in the nature of case investigation. A systematic study of the dust storm for the whole of China is still unseen and the long-term trend is unknown. The reason is that the dust storm record is usually stored in local stations and there is no statewide database of dust storms (Xu and Hu 1997). In Beijing, the windy condition usually occurs in the spring season but in the last decade of the twentieth century the spring windy condition and dust storm have weakened, compared with what happened before.

In the literature of Goudie and Middleton (1992), the following terms are used to define the miscellaneous types of dust events caused by aeolian processes:

1) Dust storms, which are the result of strong turbulent wind systems entraining particles of dust into the air, so that the visibility is reduced to 1000 m and below.
2) Dust haze, which consists of aeolian dust particles homogeniously suspended in the air. These are not actively entrained, but have been raised from the ground by a dust event that occurred prior to the time of observation or from a considerable distance. Visibility may sometimes be reduced to less than 10 000 m.
3) Blowing dust, which is the state where dust is raised above the ground locally through strong winds. The horizontal visibility may be reduced to 1000–10 000 m.
4) Dust devils or dust whirls, which are local, spatially limited, columns of dust that neither travel far nor last long.

In China, four types of dust events are usually considered in the daily observations (Central Meteorological Bureau 1979), but only the first three types of dust events are applied in investigations (Yang et al. 1997; Zheng and Zhao 1997). It is known that dust events are not only natural phenomena; they can also bring severe ecological and environmental problems (Yang et al. 1995; Ye et al. 2000). Therefore, forecasting dust events has become a major task of the China Weather Service for the public (Shanxi Meteorological Observation 1997).

Littmann (1991) studied the seasonal variations of dust storm frequency for five regions in Asia. His result indicated that the highest frequency of dust storms is located in northern China and that the peak time is in April, earlier than in other regions. However, his results were obtained from a limited number (19) of stations in China and from only 11-yr observations. Climatologically, dry regions with little precipitation appear in the Tarim Basin (Taklimakan Desert), the upper reach of the Yellow River (Gobi Desert), and the east part of Inner Mongolia. In this region, the high frequency of dust storms is identified by the satellite observation in recent years (Zheng and Zhao 1997). A long-term observation and more stations are needed to investigate the temporal and spatial distributions of dust events in China. On the other hand, it has been shown that the trajectory of dust moving was mainly along the wind direction of 850 hPa (Iwasaka et al. 1983). Because of this, the dust over Japan has its source in the region of 40°–50°N, 100°–110°E. The mechanism for the formation of a dust storm is still an open issue. One reason was suggested by Watts (1969) that in China dust storms are mainly associated with cyclone cold fronts during the surges of cold continental air masses in late winter and early spring when most of the area is under the influence of the powerful Siberian–Mongolian anticyclone. Littmann (1991) also described that globally there was no good correspondence to large circulation patterns, although most of the central Asian high-frequency areas are affected by circumpolar vortex disturbances. Based on these facts of the circumpolar vortex in central Asia, the 850-hPa dust-moving trajectory, and the surface height at 1000 m above sea level in most northwestern China, the daily 850-hPa geopotential height for the last 50 yr will be used in this investigation.

In previous investigations, limited temporal–spatial observations have been used to identify the characteristics of dust storms in China (Littmann 1991; Xu and Hu 1997). In this study, we attempt to remedy the limitation of datasets and to identify the possible mechanism of dust rising. This paper is outlined as follows. After the introduction, the datasets used are described in section 2. The climatological distributions of both dust storm and dust weather are shown in section 3. The background for the formation of dust storms and dust weather is analyzed in section 4. The spatial distributions of the correlation between dust frequency and meteorological parameters are shown in section 5. A dust index constructed by winter air temperature and spring cyclone frequency is described in section 6. Finally, the conclusions are drawn in section 7.

2. Data and methods

In this paper, all three phenomena: dust haze, blowing dust, and dust storms, are referred or defined to dust weather. Five datasets will be used. The first is the observed daily dust weather from 338 stations in China (Fig. 1) for 1954–98 based on the standard on the surface meteorological observation (Central Meteorological Bureau 1979). The days of dust events were divided according to a daily interval of 24 h from 2000 [Beijing local time BLT]. If an event of dust weather lasts past 2000 BLT, two days are counted. Contrarily, if there are several events of dust weather in a day, it is marked as one day only. In the following description, we use the terms of dust weather

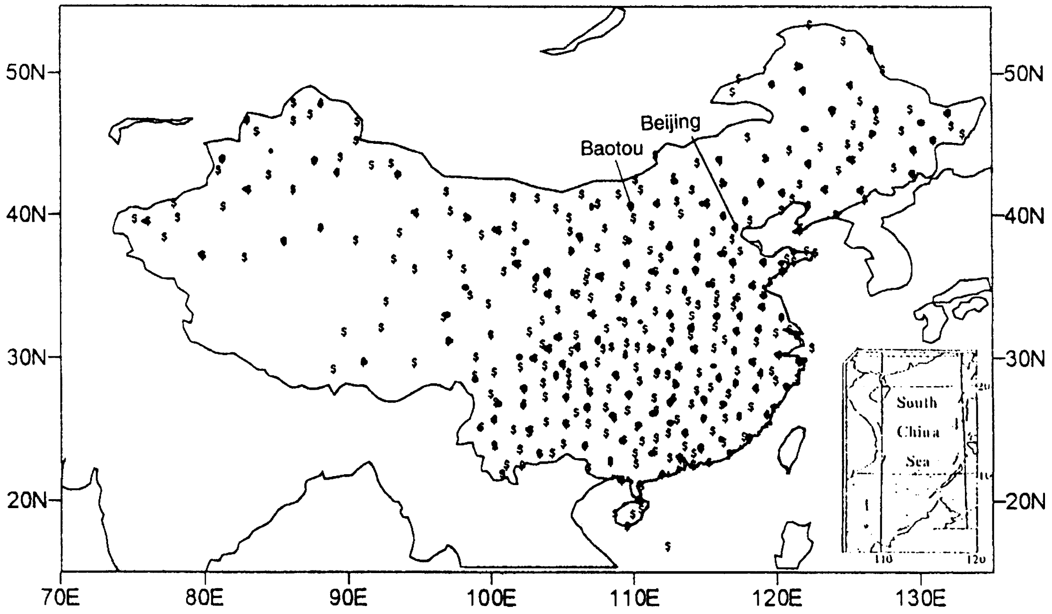

FIG. 1. Locations of 338 dust weather stations ($) and 160 temperature–precipitation stations (●) in mainland China. Stations of Beijing and Baotou used in the text are denoted.

frequency and dust storm frequency, which means the number of days of dust weather and days of dust storms that happened in one month or one year. Datasets of the dust storm and the dust weather are derived from the China Meteorological Administration.

The second and the third datasets are monthly air temperature and precipitation from 160 stations derived from the China Meteorological Administration for 1950–98. The fourth and fifth datasets are the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis of 850-hPa geopotential height and 1000-hPa air temperature from 1948 to 1999 with a horizontal resolution of 2.5°lat × 2.5°lon.

The locations of 338 dust weather stations and 160 temperature–precipitation stations are given in Fig. 1. It is easily seen that dust weather stations cover widespread regions over China except Taiwan and western Tibet. The stations of temperature and precipitation are also well scattered in various regions in China.

The spatial distribution and temporal variations of activities of surface cyclone and waves aloft are important factors for both weather and climate patterns in east Asia and other places. The cyclogenesis in the extratropics is directly linked to frontal systems and topography (Danielsen 1973). In east Asia the deep frontal system can be found in northern China and Mongolia around the year but the shallow frontal system is noted mainly in spring and summer over southern China (Zhu et al. 1981). The cyclones that appeared in northeast China are called the ''northeast China low'' while those in central-northern China including Mongolia and Inner Mongolia are called the ''Mongolian cyclone'' and the ''Yellow River cyclone.'' The cyclogenesis in northeast China and Mongolia is driven mainly by a transient baroclinic wave and its interaction with a low-level baroclinic zone (Petterssen 1956) under the adaptable topography. Some phenomena such as the surface low, cold–warm front, and precipitation can be noted from the surface map and the wave cyclone circulation (vortex) may be found at the 850- and 700-hPa levels. From the discussion above it is known that both the frontal cyclone and the vortex concerning severe weather events should have wave circulation at the lower-level atmosphere. We refer to this vortex or frontal cyclone as the ''wave cyclone.'' These wave cyclone activities are directly linked to mountains (Chen et al. 1992). The Great Xinganling Mountains located in northeast China, the Altai-Sayan Mountains in the west part of the Mongolia Plateau, and the Tianshan Mountains in the northern part of the Taklimakan Desert are some major topographies in east Asia.

The circumpolar vortices in northern China mainly include the Mongolian cyclone, the northeast China low, and the Yellow River cyclone. The activity of those cyclones in northern China is quite apparent at the 850-hPa level. The central position of a cyclone may be determined by the grid geopotential height (gph) at the 850-hPa level. The analysis procedures are listed as follows.

1) A critical value of geopotential height at the 850-hPa level for determining the cyclone center is set to 1400 or 1360 geopotential meters (gpm). Possible grid points that are lower than 1400 or 1360 gpm are identified.
2) The central location of the cyclone is determined by

the grid point whose values must be the lowest relative to its surrounding points.

3) The central location is set to the meridional and zonal arithmetic mean of all points if these points have the same values.

Among the above five datasets, only those of temperature and precipitation are from the same stations while the other datasets are from different stations. Thus, different methods will be used in different descriptions. In the investigation of the temporal–spatial distributions of dust weather or dust storms, a total of 338 stations in China are used. To discuss the relationship of dust weather or dust storms with precipitation and temperature, 160 dust weather stations that are the same as the precipitation stations are employed. To calculate the correlation coefficient between dust weather and cyclone frequency, the daily numbers of the cyclone near the stations of dust weather are counted. According to the climatological characteristic of the southeastward migration of dust weather in China, the cyclones with distances of 10° lat and 10° lon to the west and the north parts as well as those of 2.5° lat and 2.5° lon to the east and the south parts of a determined dust station are considered. The reason is that the cyclone within this domain may cause dust weather during the day.

3. Distributions of dust storm and dust weather

Using the datasets of dust storms and dust weather from 338 stations for 1954–98, the yearly mean distributions of dust storms and dust weather are shown in Fig. 2. It can be noted for the dust storm frequency that the areas above one day cover northwest China and northern China except Helongjiang Province in northeast China. The high-frequency center with the yearly dust storm of more than 30 days can be found in the Tarim Basin (Taklimakan Desert) region. Another center with the yearly dust storm of more than 15–20 days is situated in the central-western Inner-Mongolia region. In these two centers, yearly 34-day dust storms at Minfeng station in the Xinjiang region and yearly 31-day dust storms at Minqing station in the Gansu Province are observed.

A more detailed examination of Fig. 2b indicates that the yearly mean distribution of dust weather is basically similar to that of dust storms, but the domain of dust weather is larger than that of the latter. The domain with yearly 10 days of dust weather covers the Yellow River valley and northwestern China, which is consistent with the observation by satellite (Zheng and Zhao 1997). The south boundary of yearly 10 days of dust weather reaches the Yangtze and Huihe Rivers. The three dashed lines in Fig. 2b indicate the maximum of yearly dust weather. The yearly frequency of dust weather in the Tarim Basin may reach 200 days and the maximum may exceed 260 days. This frequency implies that the dust weather may be observed in any season over the Tarim Basin. Littmann (1991) indicated that dust storms might also be generated by fohnlike ''harmsil'' winds when the warm sector of a cyclone is constricted between the following cold front and the Tienshan Mountains. Temperatures may rise to 47°C when the dry air streaming down the western mountain slopes is forced to heat adiabatically (Lydolph 1977). Thus, the dust weather that happens in the Xinjiang region is obviously linked to the strong local cyclone winds and dry-thermal weather (also see Xu and Hu 1997).

4. Background for dust weather

A dry or less-precipitation climate should be the background of forming dust weather. Figure 3 shows the climatological-mean precipitation for three summer months [June–August (JJA)] based on the China rainfall dataset from 1951 to 1991. In this figure, daily precipitation from more than 300 stations has been applied to interpolate longitude–latitude gridpoint precipitation with 1° horizontal resolution over the whole of China. It is clearly seen from the figure that large precipitation not only exists in the south and east coastlands, but also appears in the upper Yangtze River (100°–105°E) with relatively less precipitation in the central-southern inland. Four maximum axes (heavy dashed lines) of rainfall can be found in far northwest China (80°–90°E), the upper reaches of the Yellow and Yangtze Rivers (100°–105°E), the east coastland (115°–120°E), and northeast China near 125°E. Between these maxima, relatively dry lines (light dashed lines) can be found in the desert region over northwest China, the midreaches of the Yellow River, and the western part of northeast China. Comparing these dry lines with the maximum of dust weather in Fig. 2b is helpful for understanding the relationship between the relatively dry background and the high frequency of the dust weather. Xu and Hu (1997) showed that the dust weather prefers to appear in the area with annual precipitation from 25 to 300 mm.

Besides the dry climate, the dynamical reason for the formation of dust weather should be the strong winds. In northern China, the cyclones can be responsible. Figure 4 shows the daily mean distributions of cyclones with the central height less than 1360 (strong cyclone) and 1400 gpm (cyclone) at the 850-hPa level. From Fig. 4a, it can be seen that three major centers with the strong cyclone activity are located in Mongolia, the northern part of northeast China, and the Sea of Okhotsk, respectively. The highest frequency center is found over the Sea of Okhotsk. The central value of 0.45 indicates the daily mean number of strong cyclone activity. In other words, there are about 163 days a year with the strong cyclone activity over the Sea of Okhotsk. In Mongolia, the center shows that there are about 110 days a year with strong cyclone activity.

By a different criterion, Fig. 4b shows the daily mean cyclone distribution with the central height less than 1400 gpm at the 850-hPa level. It should be noted that there are two centers in the Tarim Basin (far northwest

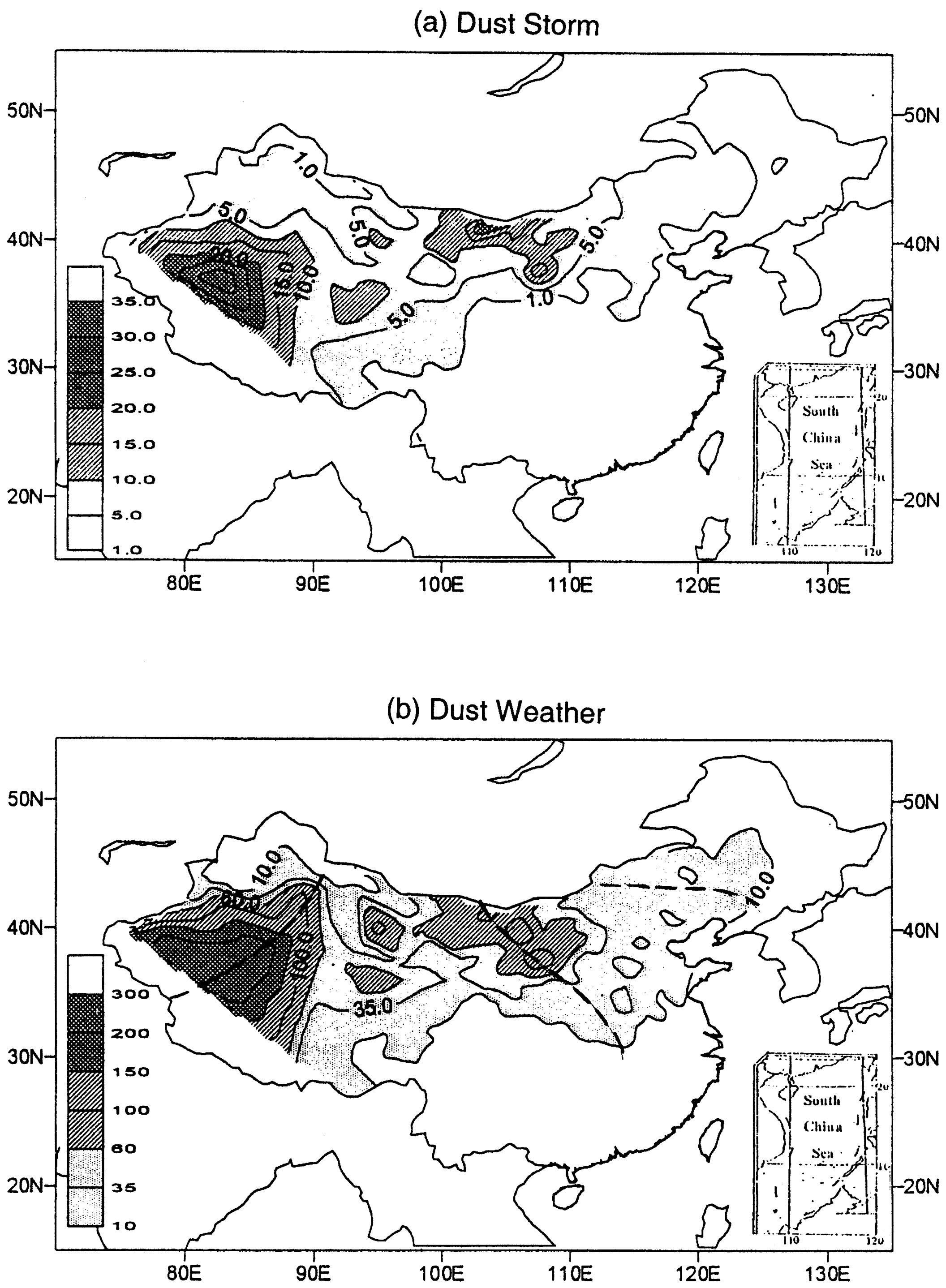

FIG. 2. Yearly mean distributions (days) of (a) dust storms and (b) dust weather averaged from 1954 to 1998. Dashed lines indicate the maximum of dust weather frequency.

China, 83°E, 40°N) and the Sichuan Basin (southwest China, 105°E, 30°N). Besides, the other three centers are the same as in Fig. 4a. In Mongolia, the cyclone activity appears half of the year. The center in the Tarim Basin denotes the geographical and dry-thermal low. The cyclone center in the Sichuan Basin concerns the geographical effect, which is called the southwest vortex in China. The southwest vortex is linked to wet and rainy conditions as can be seen from Fig. 3 in the upper reaches of the Yangtze River.

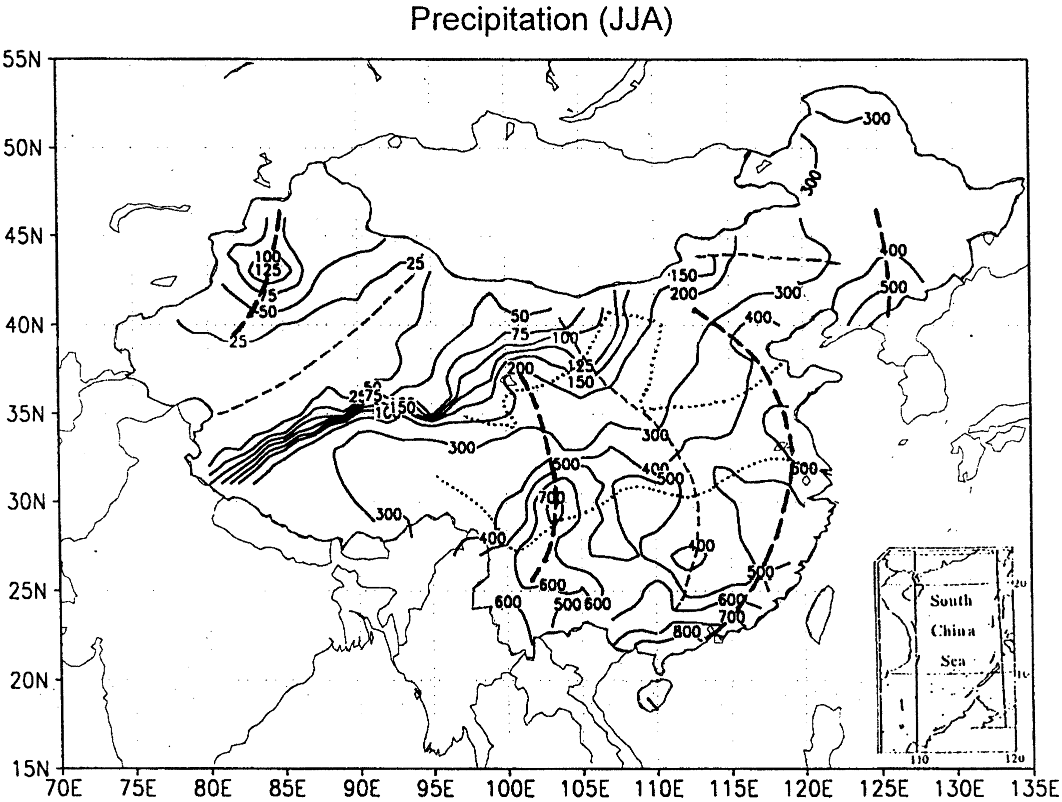

FIG. 3. Climatological mean precipitation (mm) for summer (JJA) over mainland China based on China's precipitation dataset for 1951–91. Heavy dashed line denotes the rainfall maximum and light dashed lines denote the dry lines. Dotted lines indicate the Yellow River in the north and the Yangtze River in the south.

To depict the seasonal variations, Fig. 5 presents the monthly mean days of both the strong cyclone activity and the cyclone activity constructed from the entire area (Fig. 4). The maximum numbers (65 strong cyclone days) appear in May while the minimum (37 strong cyclone days) appear in September with the central height less than 1360 gpm. The high-frequency activity of strong cyclones in April and May is consistent with the high-frequency period of dust weather (Littmann 1991). The high-frequency activity of cyclones indicated by the dashed line (a central height less than 1400 gpm) in June and July may result from both the southwest vortex in the Sichuan Basin and the dry-thermal low in the Tarim Basin.

It can be noted from Fig. 2 that the dust storm or dust weather is mainly located to the north of the Yangtze River. To examine the total trend and interannual variability of dust weather and dust storms as well as that of precipitation, temperature, and cyclone activity, we show in Fig. 6 the station-averaged means of the yearly series of three parameters. In this calculation, 83 stations of dust weather and relevant parameters to the north of 32°N have been used. A decreasing trend can be clearly seen from the yearly dust storm curve. This trend is coincident with that of the yearly cyclone days in the last 30 years. Differing from the dust storms, the dust weather exhibits a decrease frequency in 1950s and early 1960s. The high frequency of dust weather appears in the mid-1960s with the highest in 1966. Another rising period of dust weather is found in the late 1960s and early 1970s. After 1976, the frequency of dust weather starts to decrease rapidly. In the late 1980s and 1990s, the frequency of dust weather reaches a low value, which is only one-fifth, compared to that in the 1950s–1960s. The interannual variability is dominated in the series of dust weather, cyclone, precipitation, and temperature except that the increasing trend is seen from the temperature series and the decreasing trend from the dust storm series.

Table 1 shows the correlation coefficients among the different parameters related to dust weather and dust storms. In particular, the correlation between dust weather and the cyclone frequency is 0.415, significant at the 99% confidence level. It can be seen from Fig. 6 that the yearly temperature is gradually increasing since the 1970s. As indicated by Chen et al. (1998), the winter warming has a positive contribution to the annual temperature. The correlation coefficient between the yearly temperature and yearly dust weather frequency is -0.677. Different from the above, the coefficient between the yearly precipitation and dust weather frequency is only -0.141. Comparing the coefficients in

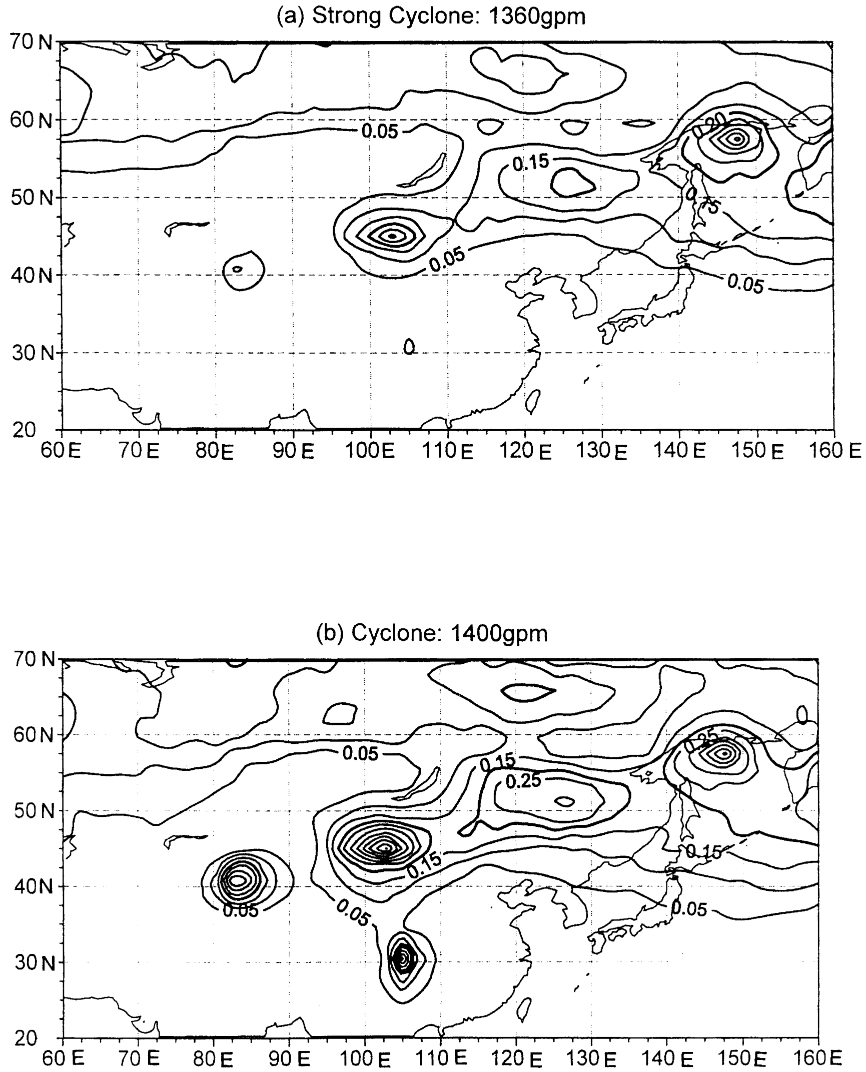

FIG. 4. Daily mean distribution (day^{-1}) of (a) strong cyclone activity with the central height less than 1360 gpm and (b) cyclone activity with the central height less than 1400 gpm at the 850-hPa level.

Table 1, it can be found that the lower air temperature in the prior winter (DJF) and the high-frequency cyclone in spring (MAM) contribute mainly to the dust weather and dust storm conditions.

5. Spatial distribution of correlation

General relationships among temperature, precipitation, and cyclone frequency corresponding to dust storms and dust weather have been illustrated above. In this section, we will show their spatial distributions of correlation locally. Figure 7 plots the spatial distributions of correlation coefficients from different pairs of parameters. It can be seen from Fig. 7a, which shows the correlation distribution between the yearly dust weather frequency and cyclone frequency in China, that the positive correlation with the coefficient larger than 0.30 appears over Inner Mongolia, northeast China,

TABLE 1. The correlation coefficients among dust storm (dust weather) and parameters (temperature, precipitation, and cyclone frequency) in northern China.

	Annual precipitation	MAM precipitation	DJF precipitation	Annual temperature	MAM temperature	DJF temperature	Annual cyclones	MAM cyclones	DJF cyclones
Dust storm	−0.103	0.104	−0.102	−0.666	−0.467	−0.603	0.671	0.560	0.154
Dust weather	−0.141	0.010	−0.102	−0.677	−0.381	−0.643	0.415	0.393	0.282

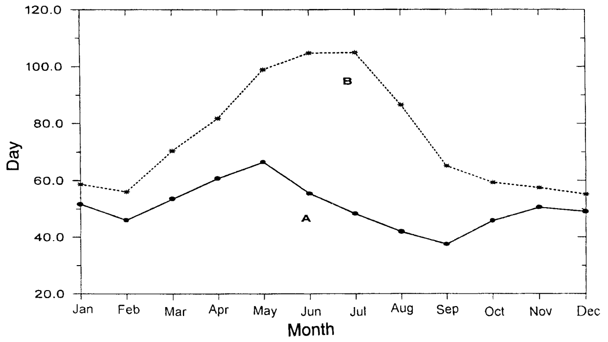

FIG. 5. Climatological monthly mean days of cyclone activity in east Asia. Curves (A) and (B) indicate the strong cyclone and cyclone, respectively.

north China, and the east Tibetan Plateau, respectively. A comparison of Fig. 7a with Fig. 2b indicates that the high frequency of dust weather corresponds to the cyclone activity. On the other hand, the formation of dust weather needs two conditions: one is dry-climatic background and the other is cyclone activity. In northern China, the Mongolian cyclone may be a major dynamical condition for this formation. Despite the high-frequency center of dust weather in the Tarim Basin, the correlation coefficient is low due to the few deep cyclones or circumpolar vortexes over there.

Figure 7b displays the distribution of correlation coefficient between dust weather frequency and temperature. The negative correlation mainly dominates over northern China with a value of -0.4 covering the region from the Hexi Corridor and the Loess Plateau to Beijing in north China. This figure indicates that the cold air activity in eastern China, particularly north of the Yangtze River, may be an important factor for the formation of dust weather. The dust weather here does not have a close relationship with the temperature in western China.

The distribution of correlation coefficients between dust weather and precipitation can be seen from Fig. 7c. Table 1 shows that there is little relationship between dust weather and precipitation. A weak relationship can also be found in Fig. 7c except a value of -0.30, which has passed the 95% confidence level, in the Xinjiang region. It is noteworthy that the deficiency of precipitation in the Xinjiang region may be a vital condition for the formation of dust weather.

Similar results shown in Figs. 7a and 7b have also been obtained when we calculate the correlation only for spring. The significant relationship between dust weather and the cyclone, as well as that between dust weather and tem-

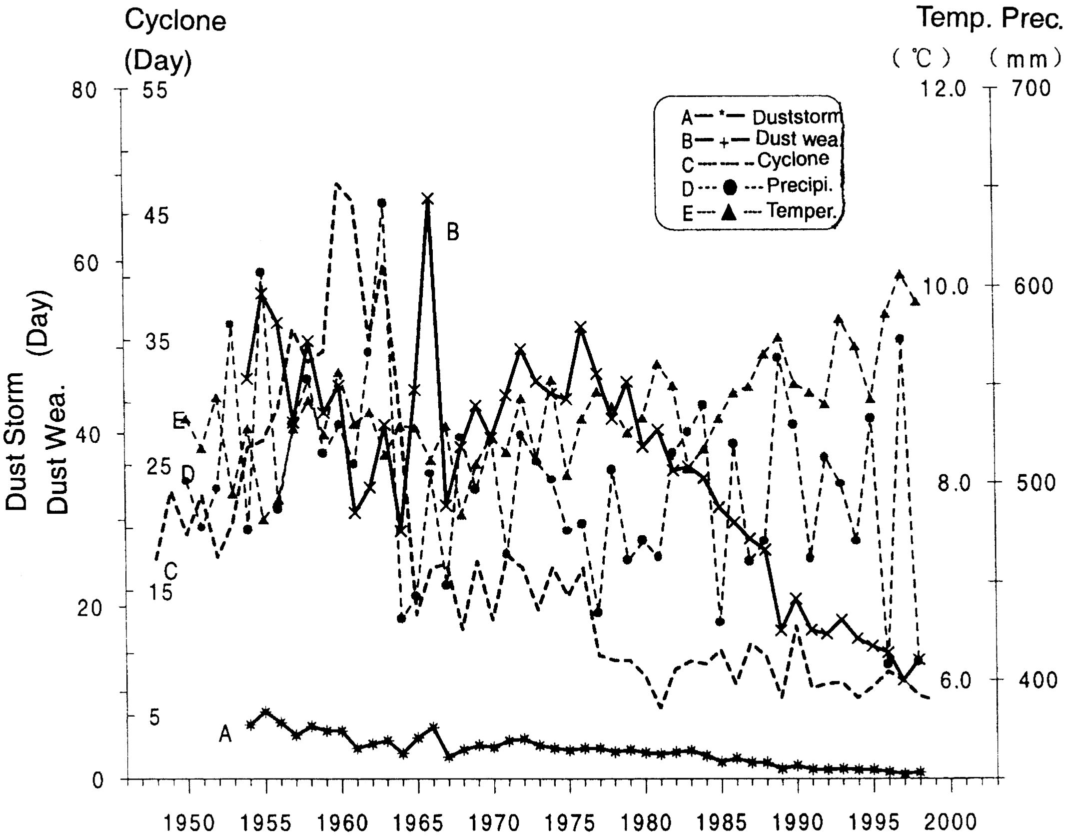

FIG. 6. Yearly mean series of dust weather (days), dust storms (days), precipitation (mm), temperature (°C), and cyclone activity (days) in the north of the Yangtze River for averaged stations.

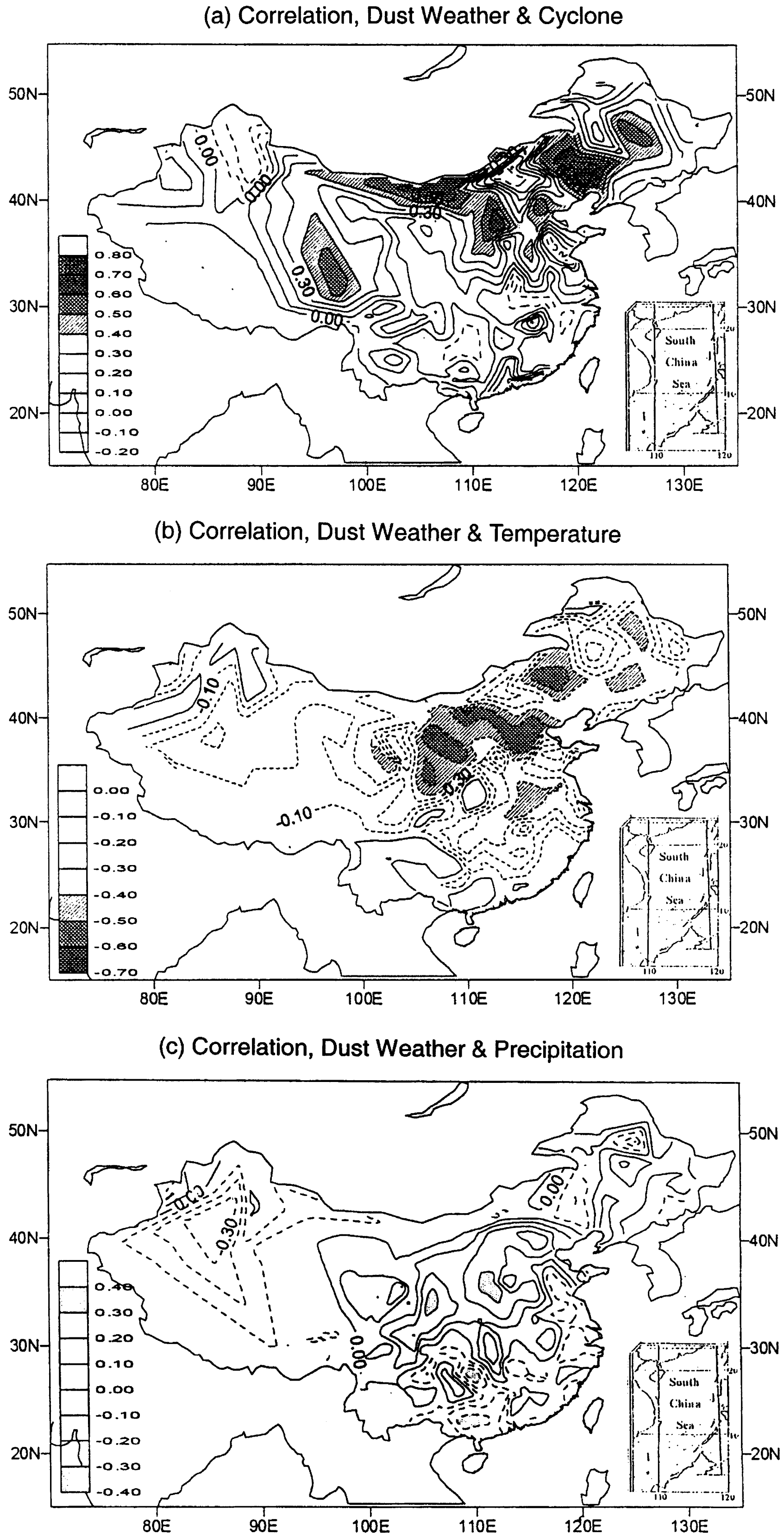

FIG. 7. Spatial distributions of correlation from different pair parameters between: (a) yearly dust weather frequency and yearly cyclone frequency, (b) yearly dust weather frequency and yearly air temperature, and (c) yearly dust weather frequency and yearly precipitation.

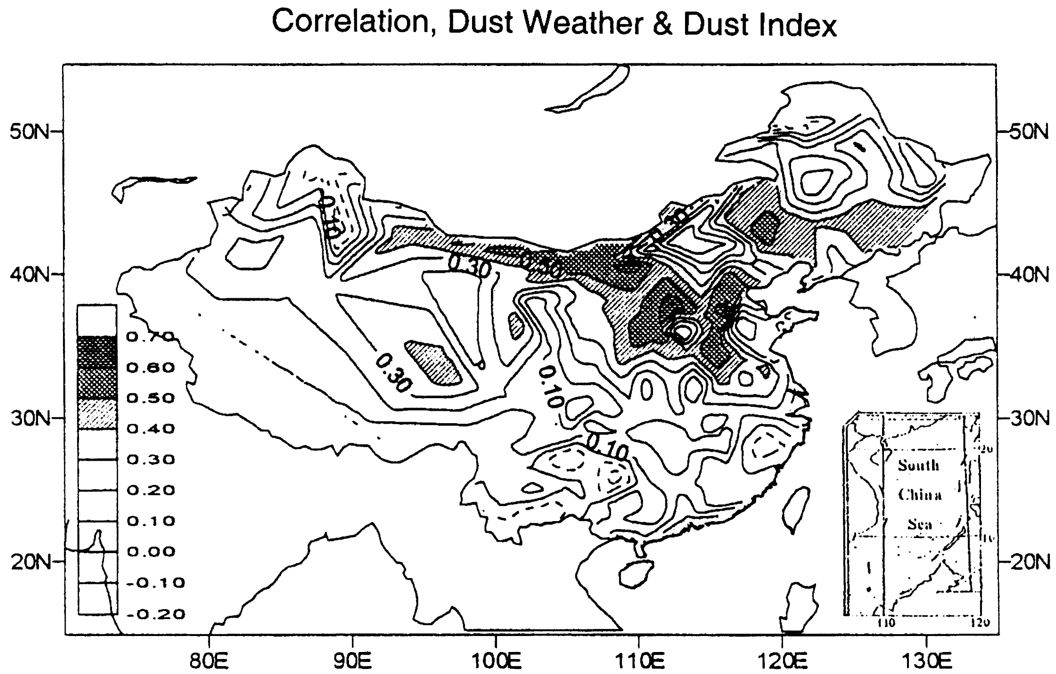

FIG. 8. Spatial distribution of correlation coefficients between dust weather frequency and the dust index in mainland China.

perature, indicates that the cyclone and its strong cold surge are responsible for the formation of the dust storm. In China, dust weather mainly appears from March to May, with a peak in April. This is why we focus on the activity of the cyclone cold surge in spring.

6. Dust index and discussion

In northern China, except western China including the Xinjiang region, the air temperature in winter and the cyclone frequency in spring are the two important factors for the formation of spring dust weather. Two physical causes can be put forward. First, if the sand soil is heavily frozen under the lower winter temperature, it is easier to become desertificated after melting in spring. Second, the more cyclones in the spring, the larger frequency of dust weather, through dynamical effects. Yang et al. (1997) noted that the track of dust weather is the same as that of the cold surge. This is in good agreement with the frequency distribution of dust weather and the distribution of the correlation coefficient between dust weather and cyclone frequency.

According to the relations among dust weather, winter air temperature, and spring cyclone frequency, an index of dust weather (or dust index) can be defined as

$$\mathrm{DI} = r_C \frac{\Delta C}{\delta_C} - r_T \frac{\Delta T}{\delta_T},$$

where, ΔT, ΔC and δ_T, δ_C are the temperature anomalies in the prior winter season (DJF), the departure of spring (MAM) cyclone frequency, and their standard deviations, respectively; r_C and r_T are the weighting coefficients of cyclone frequency and temperature. The weighting coefficients may vary from different stations and different periods.

In this paper, we take $r_C = 1.0$ and $r_T = 1.0$ because the prior winter air temperature and spring cyclone frequency corresponding to the dust weather have similar relations. It can be understood from the definition of the dust index that the frequency of dust weather is directly proportional to the index. Figure 8 is the spatial distribution of the correlation coefficient between dust weather frequency and the dust index. It is worthy to note that the dust index is good to represent dust weather in the domain north of the Yangtze River and east of 90°E, particularly in the Inner Mongolian region and north China. In these areas, the correlation coefficient has exceeded the value of 0.50 at a confidence level over 99%. Another high correlation is in the southern part of northeast China. The weak relationship in the Xinjiang region over far northwest China can be understood by the small relationship shown in Figs. 7a and 7b.

To examine the relation between dust weather frequency and the dust index in more detail, we show in Fig. 9 the three parameters (dust index, dust storm frequency, and dust weather frequency) at the stations in Beijing and Baotou, respectively. It can be seen that the long-term trend and interannual variability are rather remarkable and consistent with each other except for a few years. Comparing Figs. 9a with 9b, it can be found that the frequency of dust weather and dust storms in Baotou is higher than that in Beijing. During the 1950s–

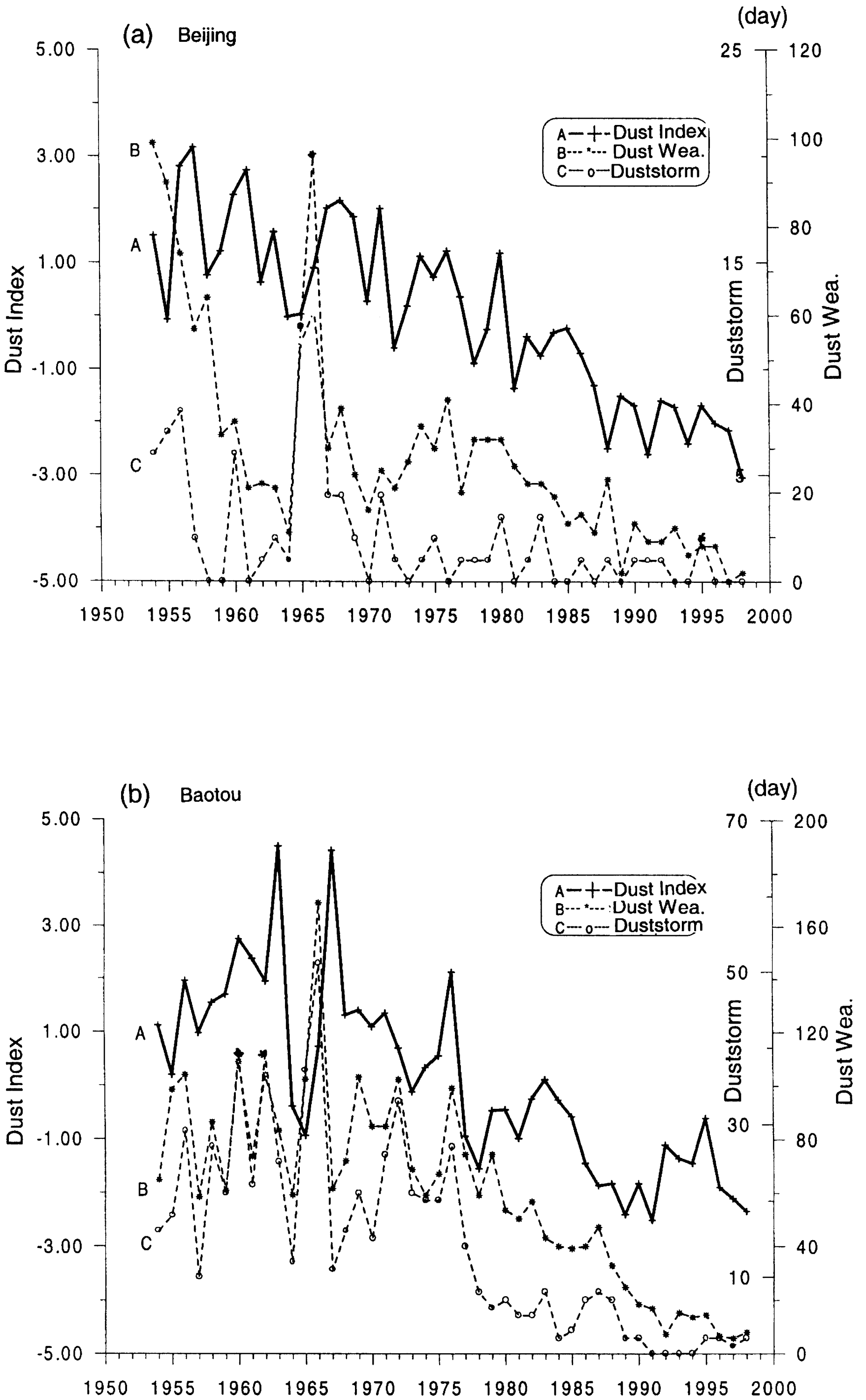

FIG. 9. Yearly series of the dust index, dust storm frequency (days yr^{-1}), and dust weather frequency (days yr^{-1}) at the stations of (a) Beijing and (b) Baotou.

1970s, the frequency of dust weather and dust storms in Baotou is rather high. This may be due to the fact that the Gobi Desert is located nearby. Since the mid-1970s, the dust storms obviously decrease and a difference between dust storms and dust weather in Baotou implies that many dust cases come from other places. In the last two decades, warm-dry climate is observed in north China (Qian and Zhu 2001). The fact that less dust weather has prevailed in this period may be due to relatively higher winter temperatures and fewer spring cyclones.

To better understand the high frequency of dust

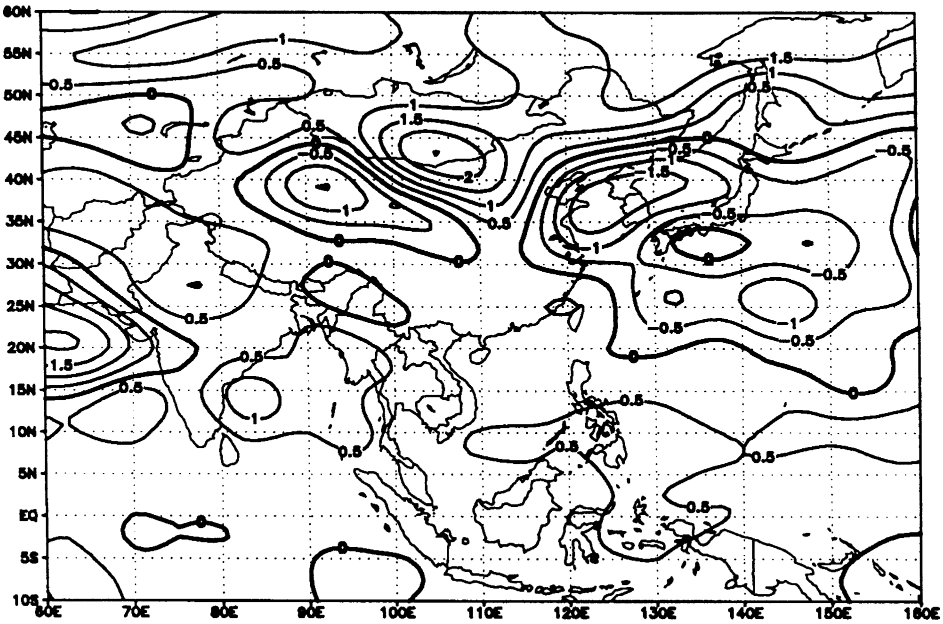

FIG. 10. Distribution of temperature difference (°C) by 1985–97 − 1958–70 in east Asia.

weather before the mid-1970s, we show in Fig. 10 the distribution of 1000-hPa air temperature difference between 1985–97 and 1958–70. The warming in the period 1985–97 is significant in high latitudes with a center in Mongolia. Two cooling centers in northwestern China and the Korean Peninsula related to the period 1958–70 can also be seen. This distribution of temperature difference is consistent with that shown by Nicholls et al. (1996). The warming in Mongolia and cooling in northern China reduced the meridional temperature gradient so that the thermal front becomes weakened in the recent decades, resulting in the reduced cyclone frequency in northern China. This one of the reasons why the reduced cyclone frequency and dust weather in recent decades may be the change of temperature contrast in Mongolia and northern China.

7. Summary

1) The source places of dust storms are mainly the desert regions in northern China. The highest frequency of dust storms is found in the Tarim Basin and the second highest is located in the central part of Inner Mongolia. The high-frequency center of dust storms is basically consistent with that of dust weather in northern China. Two extension zones of dust weather have been noted from central Inner Mongolia to the lower reaches of the Yangtze River and from eastern Inner Mongolia to central northeast China. The yearly frequency of dust weather in the Tarim Basin may reach 200 days and the maximum may exceed 260 days. This frequency implies that dust weather may be observed in any season over the Tarim Basin.
2) Climatologically, there are four maximum axes of rainfall in far northwest China (80°–90°E), the upper reaches of the Yellow and Yangtze Rivers (100°–105°E), east coastland (115°–120°E), and northeast China near 125°E for summer. Between them, relatively dry zones can be found in the desert region over northwest China, the midreaches of the Yellow River, and the west part of northeast China. These dry zones are the background of not only dust storm formation but also dust transmission due to the fact that the dry earth surface and dry air are hard for dust sand to deposit.
3) The circumpolar vortex disturbances observed in northern China, Mongolian cyclone, the northeast China cyclone, and the Yellow River cyclone, are important for dust storm activity. The activity of those cyclones is quite apparent at the 850-hPa level, with the frequency peak in May, a high-frequency period of dust storm activity as well.
4) There has been a definite relationship between dust weather and meteorological parameters in different regions over China. The significant positive correlations between dust weather frequency and cyclone days is found from central Inner Mongolia to north China and from eastern Inner Mongolia to central northeast China. Both less-precipitation and strong cyclone winds characterize these two significant zones. The significant negative correlation between air temperature and dust weather frequency is located in north China, northeast China, and east China, which means that cold-dry air is vital for the formation of the dust weather in the eastern part of China. Different from above, there is no significant

correlation between precipitation and dust weather in the eastern part of China, whereas a significant negative correlation is found in the Xinjiang region.

5) There have obviously been interannual variability and long-term trends among dust storm frequency, dust weather frequency, air temperature, and cyclone frequency in northern China. In the eastern part of China, the frequencies of dust storm and dust weather in the 1950s–1970s are about twice as those after the mid-1980s. This may be because the warming in Mongolia and cooling in northern China reduce the meridional temperature gradient, resulting in the reduced cyclone frequency in northern China.
6) The constructed dust index using winter temperature and spring cyclone can well represent dust storm activity in northern China, particularly in the regions from central Inner Mongolia to north China and from eastern Inner Mongolia to central northeast China. The physical meaning of the dust index in the eastern part of China can be understood from the fact that the dry background, dry-cold surge, and strong cyclone winds are favorable for causing the dust storm or for forming dust weather. According to this dust index, the dust weather may be predicted since both the winter temperature and the spring cyclones are the two important precursors.

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