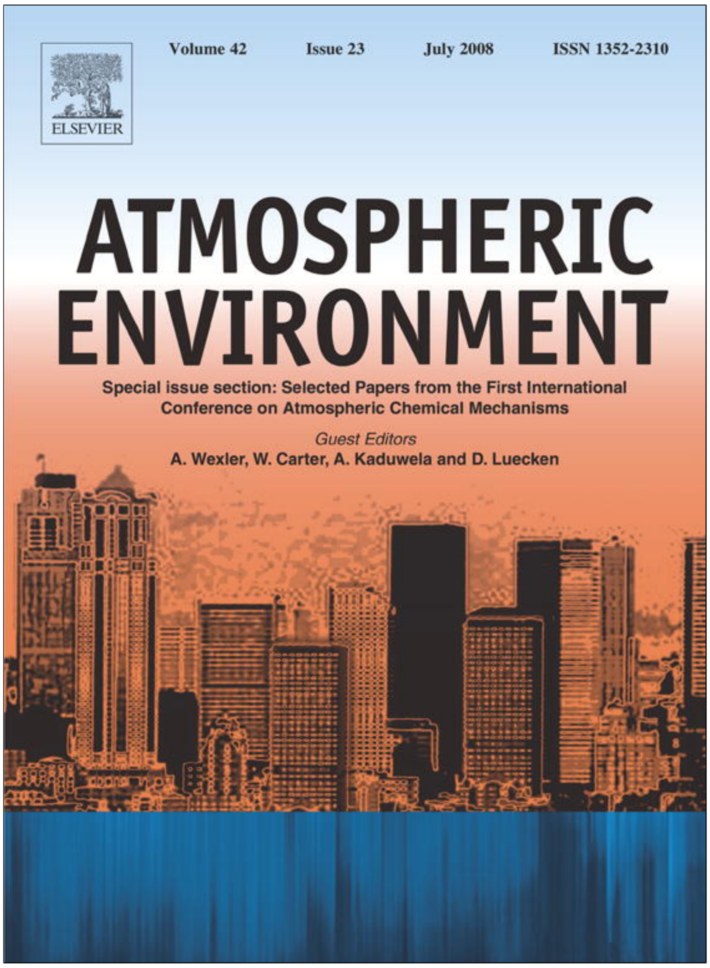
Volume 42
Issue 23
July 2008
ISSN 1352-2310
ELSEVIER
ATMOSPHERIC ENVIRONMENT
Special issue section: Selected Papers from the First International Conference on Atmospheric Chemical Mechanisms
Guest Editors
A. Wexler, W. Carter, A. Kaduwela and D. Luecken

Atmospheric Environment 42 (2008) 5896–5904

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

The properties of dust aerosol and reducing tendency of the dust storms in northwest China

Peijian Fu [a,*], Jianping Huang [a], Chunwei Li [a], Sharon Zhong [b]

[a] College of Atmospheric Sciences, Lanzhou University, Tianshui Street 222#, Lanzhou 730000, PR China
[b] Department of Geography, Michigan State University, East Lansing, MI 48824, USA

A R T I C L E I N F O

Article history:
Received 15 January 2008
Received in revised form
12 March 2008
Accepted 19 March 2008

Keywords:
Asian dust storms
Northwest China
Mass concentration and optical properties of the dust aerosol
Climate change

A B S T R A C T

Since 2004 the dust aerosol observation has been carried out in Minqin Weather Station, located on the boarder of the source region of Asian dust storms (ADS). We obtained current data throughout the consecutive 3 years of observation, from January 2004 to December 2006, with advanced equipment (a particulate mass concentration of PM-10 monitor, a FD12 visibility meter, an integrating nephelometer and a robotic photometer) and also the regular data on dust storms collected in the past 50 years from 168 weather stations of northwest China to analyze the averaged mass concentration of dust aerosol and its optical properties for both dust storms and clear days. We defined the intensity index of dust storms (IIDS) to describe the intensity of a dust storm and TIIDS to describe for yearly intensity of dust storms. The temporal and spatial distribution of the indices show a decreasing trend of the intensity of dust storms in the past 20 years. This decreasing trend was correlated with the temperature anomalies in the same period in northwest China. The conclusion is that rising temperature depresses intensity of the cold flows from North Mongolia, which often trigger dust storms in Gobi Desert.

1. Introduction

Asian dust storms (ADS) are known to be a major air pollution source. ADS have strongly affected the environment of human beings in many aspects: they interrupt the balance of radiation, accelerate the desertification and degrade the ecological system in Asian arid regions that are usually thought as the main sources of dust storms (Jigjidsuren and Oyuntsetseg, 1998). The effects of environment of ADS are causing concern worldwide (Moria et al., 2003; Natsagdorja et al., 2003).

In the dry season, strong winds blow dust high into the atmosphere to form ADS, and westerly upper level winds bring fine dust from west to the east or southeast to form regional brown clouds. Hundreds of tons of dust fall along the path to Pacific Ocean and its western coast (Xuan et al., 2004; Zhang, 2001), and affect the air quality over a large region. Zhang (2001) estimated that about 800 Tg of dust from Asian arid/semi-arid region (mainly from Gobi desert) are discharged into the atmosphere annually, which may be half of the dust generated around the world and have a great adverse influence on human health (Dockery and Pope III., 1994; Ostro et al., 1999; Kwon et al., 2002). Moreover, dusts floating in the air absorb and scatter solar radiation directly, altering regional radiation balance and affecting atmospheric stability, vertical motions, the large-scale circulation and hydrologic cycle, with significant regional climate effects (Menon et al., 2002).

The recent images from the satellites showed that the radius of cloudy droplet is much smaller over land than over ocean, for the reason that the aerosols with high density over land compete with air moisture, making it difficult to form rain (Breon et al., 2002). This phenomenon is explained as the effect of air dust on rain formation. Therefore ADS have played an extremely

* Corresponding author. Tel.: +86 13893205268.
E-mail address: fupj@lzu.edu.cn (P. Fu).

1352-2310/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2008.03.041

important role in climatology, weather forecasting, and biogeochemical cycling (Zhang 2001).

Since the sources of ADS have all been found in remote areas, few observational data are available for research. Many of their characteristics remained unknown. It is necessary to investigate properties of ADS in source area so we can evaluate the influence of ADS on human beings and their environment more accurately.

Gobi Desert is one of the most important sources of ADS. Most of the desert is in northwest of China (Ying and Chien-Lung, 2006) (Fig. 1). There are about 200 weather stations around this area. The routine work of those weather stations was to record dust storms when storms came and the recorded data included starting time, duration, atmospheric visibility, maximum wind speed and direction, humidity and precipitation. These data are very simple, but recorded for a long period, >50 years. Starting from late 2003 a number of new observations on dust aerosols have been carried out with the help of advanced equipment in Minqin Weather Station (38.63N, 103.08E, 1368 m), the closest station to Gobi Desert (Fig. 1). The observations include the mass density of dust over the ground, scattering coefficient, visibility and aerosol optical depth. The combination of these advanced measurements and the long-term climate data allow a better characterization of ADS.

The purpose of our work is to analyze mass concentration of dust aerosol and its variation for both ADS weather and clear days in Minqin, to understand the radiative effect of ADS, and to describe the temporal and spatial distribution of the intensity of ADS in the past 50 years in northwest China with an intensity index of dust storm (IIDS) and total of IIDS (yearly accumulated IIDS; TIIDS). Both IIDS and TIIDS can be calculated with the regular data and they provide a summary of the statistical characteristics of the dust events over the Gobi Desert and its surroundings.

2. Situation of measurements and instruments in Minqin

Minqin is in the frontier of Gobi Desert in dry climate with an annual precipitation 100 to 200 mm and an average relative humidity <40%. Temperature in the region fluctuate significantly every season and even individual days. The annual average temperature is lower than 10 °C. Every year the sand dunes are moving about tens of meters closer to Minqin, seen from its northwest and northeast border. Minqin is like a peninsular in a sand sea and becomes the most affected areas by dust storms and sand dunes in China.

In addition to the regular observations of dust storm, several automatic instruments were mounted in Minqin Weather Station for monitoring the dust aerosol continuously. A TEOM 1400a particulate mass concentration of PM-10 monitor from Rupprecht & Patashnick, a FD12 visibility meter from Vaisala, an Ecotech M9003 integrating nephelometer and a CIMEL CE 318 robotic photometer were introduced to help monitor ADS in this area.

The TEOM 1400a particulate monitor has a filter permitting particles smaller than 10 μm in diameter to pass. At the heart of the device is the tapered element oscillating microbalance, which is a patented inertial mass measurement technique for making a direct measurement of the particle mass collected on a filter in real time. The monitor is mounted on a 2-m shelf, taking each sample every 5 min.

The FD12 forward-scatter visibility meter evaluates the meteorological optical range (MOR) by measuring the scatter of infrared light in the air. Fast pulse rate used

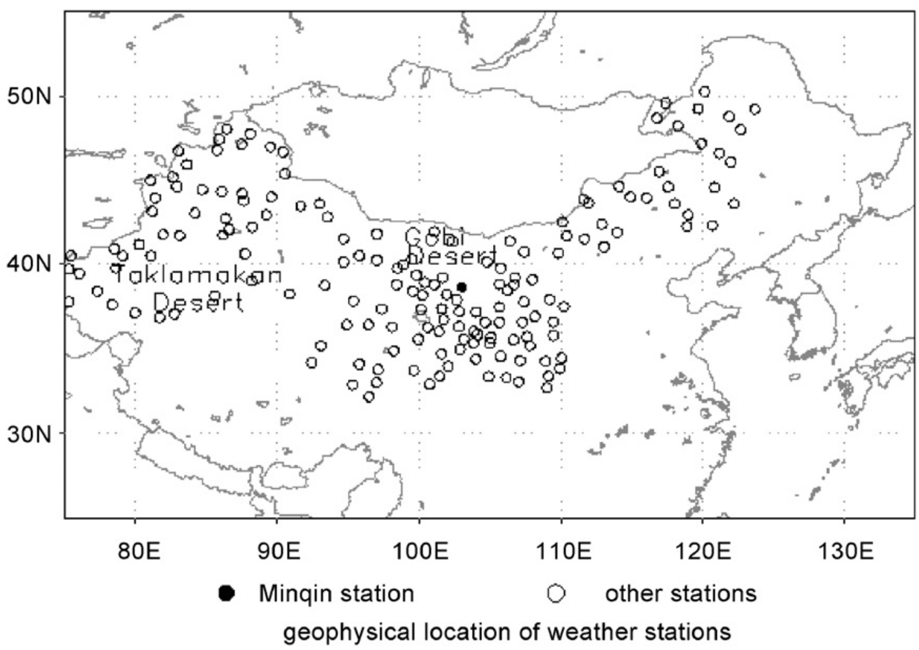

Fig. 1. Geographical location of Minqin Weather Station and the other weather stations with ADS observations.

enables precise recognition of weather conditions. The device has a built-in visibility calculation compensation for snow, fog, rain, and sleet. The design of the device includes elimination of effects of stray light going into the chamber in bad weather, assuring accurate measurements under all circumstances. Each sample was taken at the same frequency as that of the TEOM 1400a particulate meter.

The Ecotech M9003 integrating nephelometer uses the light scattering coefficient of particles to measure fine particulate matter. It shows excellent correlation with PM2.5 reference methods. The light source is a reliable and stable LED that emits light at a fixed wavelength and facilitates a wide measuring range of scatter coefficient (from $<0.25\,\mathrm{M\,m^{-1}}$ to $>2000\,\mathrm{M\,m^{-1}}$). Its measurement frequency is the same as that of the TEOM 1400a particulate meter.

The Cimel CE 318-2 robotic sun photometer was used to calculate aerosol optical depth of total atmosphere and Ångström index (Holben et al, 1998). It is an automatic tracking sun photometer measuring sun and sky luminances in 8 filters, ranging from visible to near infrared wavelengths, with filters at 440, 675, 870, three 870 nm polarized filters and 1020 nm for measuring atmospheric aerosol optical thickness, and a filter at 939 nm for measuring atmospheric water vapor. The instrument automatically computes the position of the sun and traces its movement.

3. Data analysis method

3.1. The temporal variation of dust aerosol mass concentration and the tendency of the intensity of dust storm in Minqin

According to guidelines set by the Chinese Meteorological Observations, a dust storm is recorded when the horizontal visibility at the ground is <2 km in a dust weather with the instantaneous wind speed $>10\,\mathrm{m\,s^{-1}}$. From January 2004 to December 2006, there were a total of 39 dust storms that occurred in Minqin and its surroundings (Table 1). The maximum duration of the dust storm was >10 h, on 3 February 2004; the minimum was about 11 min, and the average was 2 h during this 3 year period (Table 2). The average of the data measured in dust storms and clear days in 3 years is shown in Table 2. The maximum frequency of dust storms occurred in February, which accounted for 23% of overall occurrences. There were no dust storms in the fall season (September, October, November), and in early winter months (January and December). Fig. 2 provides the monthly average mass concentration of dust aerosol for dust storms and for clear days. The variation of the monthly average of mass concentration was from about 1.14 to $5.04\,\mathrm{mg\,m^{-3}}$ in dust storms and from 0.10 to $0.38\,\mathrm{mg\,m^{-3}}$ in clear days.

In order to analyze the tendency of dust storms over the past 50 years, we define the IIDS to describe the intensity of a dust storm recorded in a weather station, and it can be calculated by regular data. The definition of

Table 2
Average value of the data in dust storms and in clear days from 2004 to 2006 measured in Minqin

Measurements	In dust storms	In clear days
Mass density of air ($\mathrm{mg\,m^{-3}}$)	2.50 ± 2.12	0.10 ± 0.05
Wind speed ($\mathrm{m\,s^{-1}}$)	11.27 ± 1.85	2.6 ± 1.60
Visibility (km)	2.08 ± 1.03	16.19 ± 11.22
Scatter coefficient ($\mathrm{M\,m^{-1}}$)	2385.76 ± 2327.55	209.68 ± 180.70
Aerosal optical depth	3.06 ± 1.68	0.25 ± 0.20
Ångström exponent index	0.32 ± 0.09	2.13 ± 0.55
Average duration of a dust storm (min)	120.60 ± 87.74	

Table 1
Information about beginning time and duration of each dust storm from January 2004 to December 2006 in Minqin

2004			2005			2006		
Date	Time[a]	Duration[b]	Date	Time[a]	Duration[b]	Date	Time[a]	Duration[b]
3-Feb	9:09	624	21-Feb	11:56	124	12-Feb	16:23	11
4-Feb	18:52	57	23-Feb	10:13	108	20-Feb	9:08	79
12-Feb	13:05	180	18-Apr	10:21	11	3-Mar	11:02	212
19-Feb	10:30	41	14-May	16:55	117	9-Mar	11:02	247
24-Feb	12:09	354	15-May	18:52	78	5-Apr	17:27	31
2-Mar	13:18	210	28-May	7:17	185	10-Apr	5:25	308
4-Mar	10:13	64	25-Jun	19:36	51	24-Apr	8:07	17
31-Mar	12:22	41	17-Jul	10:34	197	15-May	9:36	50
28-Apr	5:38	145	18-Jul	17:32	80	25-May	10:57	91
24-May	19:32	455	19-Jul	18:52	30	5-Jun	18:28	24
26-Jun	17:28	84				6-Jun	18:52	75
27-Jun	18:52	57				17-Jun	2:35	42
28-Jun	16:34	138				16-Aug	18:27	25
29-Jun	18:52	80				17-Aug	18:52	15
8-Jul	0:07	66						

[a] Time: the beginning time of a dust storm in local solar time.
[b] Duration: the duration of a dust storm in minutes.

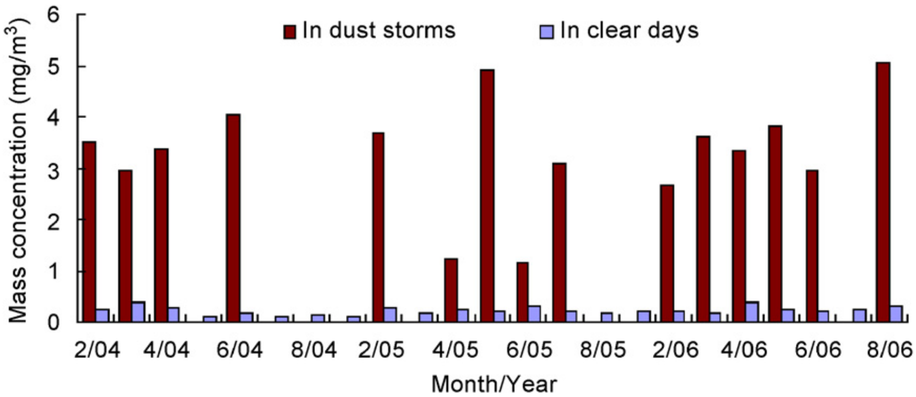

Fig. 2. The monthly average of the mass concentration of dust aerosol in dust storms and clear days over Minqin from 2004 to 2006.

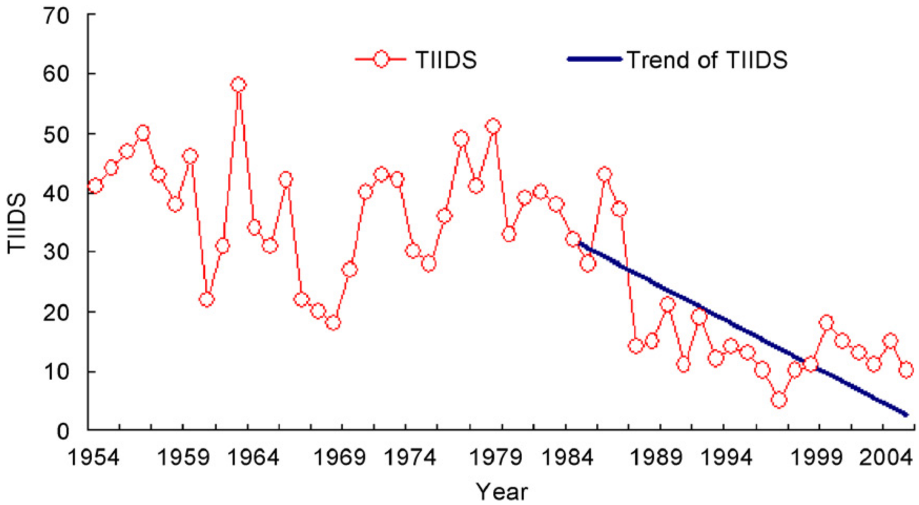

Fig. 3. The temporal variation and the tendency of the TIIDS of Minqin.

IIDS is the following:

$$\text{IIDS} = \frac{n}{N}\frac{u}{\overline{U}}\frac{t}{\overline{T}} \tag{1}$$

N is the total number of weather stations in a radius of 400 km from the recorded station; n is the number of the stations in this range which also recorded the dust storm in the same time ($n \leqslant N$); u and $\overline{U}$ are the wind speed in the dust storm and the average wind speed of the total dust storms, respectively (m s^{-1}); t and $\overline{T}$ are the duration in minutes of the dust storm and the average duration of the total dust storms. The IIDS values are accumulated for an entire year to form **TIIDS (total of IIDS in one year), a quantity that describes the annual intensity of dust storms for a particular location.

Fig. 3 shows the temporal variation of TIIDS in Minqin. There is a large scatter in TIIDS and the trend of TIIDS was decreasing (Fig. 3) in Minqin, especially in the past 20 years. This decreasing trend has also been identified by Wang et al. (2007), using different indices (Gobi dust index: GDI and Taklamakan dust index: TDI). Why could there be a decrease of the intensity of the dust storms in the past decades? Are some environmental factors correlated with the decrease? We will discuss the matter in a later section.

3.2. *The optical properties and radiation effects of the dust storms*

Robotic sun photometer (Cimel CE 318-2) is used to get the atmospheric optical depth. The optical depth is proportional to the concentration of aerosol in the atmosphere, which absorbs and scatters the direct solar radiation. With the optical depth, the radiation effect of dust can be estimated. In order to eliminate the effect of the clouds on the measurements of the aerosol optical depth, the sun photometer by Cimel was designed to screen data automatically in bad weather or in dust clouds and therefore no data were recorded in the strong dust storms.

The optical depth of dust aerosol has a close correlation with the visibility as shown in Fig. 4 ($R^2 = 0.95$). With the visibility data from the FD12, the optical depth of dust aerosol can be estimated in bad weather by the formula as in Fig. 4.

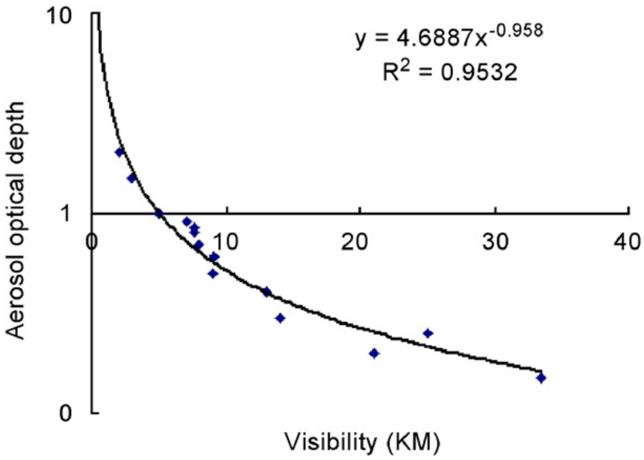

Fig. 4. The correlation between aerosol optical depth taken from the Cimel CE 318-2 and visibility taken from the FD12.

Figs. 5 and 6 show the visibility and the optical depth in dust storms and in clear days, respectively. The average optical depth (2 visible waves and 5 infrared wavelengths: 440, 675, 870, three polarized of 870 and 1020 nm) in dust storms is 3.06, which is >10 times of that in clear days, 0.25. The average visibility in dust storms is 2.08 km, about one eighth of the clear-day value 16.19 km. The average scattering coefficient in dust storms is 2385.76 $\mathrm{M\,m^{-1}}$, >10 times of the value 209.68 $\mathrm{M\,m^{-1}}$ in clear days.

During daytime, high mass concentration of dust aerosol can largely reduce the solar radiation on the ground by scattering and absorbing radiation. The daily variation of the total solar radiation measured in Minqin weather station under the typical weather, both on dust days on clear days, is shown in Fig. 7. In 3 February 2004, the dust storm started at about 9:09 AM and ended in the evening, and it lasted >10 h. The daily rise of the concentration of PM-10 was synchronized with the reduction of the total solar radiation. During the storm, the total solar radiation on the ground was nearly reduced to only a half of the clear-day value (2 February 2004).

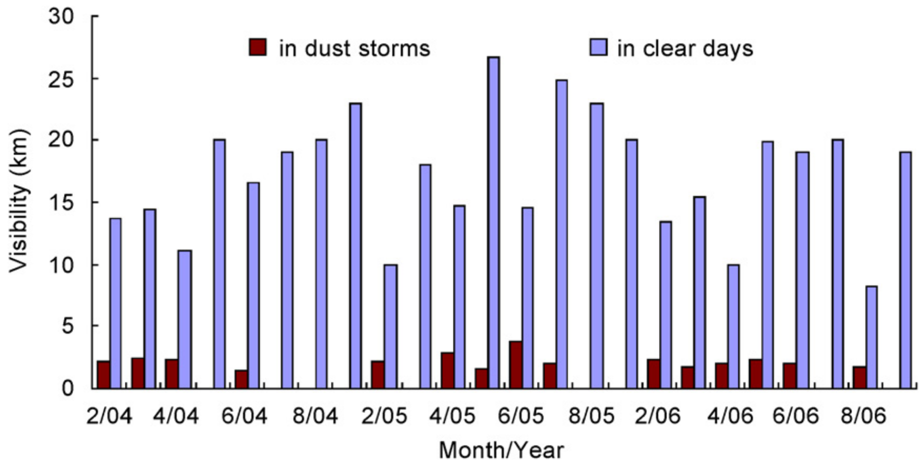

Fig. 5. The monthly average of visibility in dust storms and clear days.

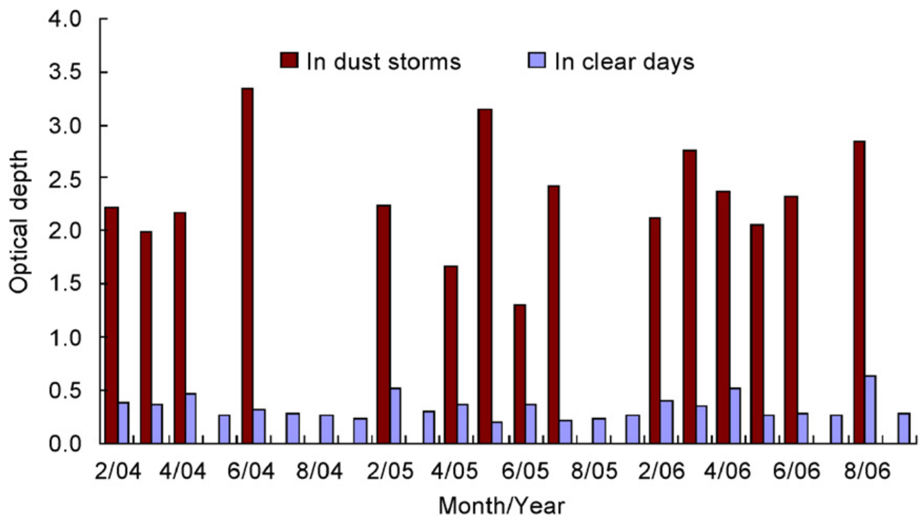

Fig. 6. The monthly average of optical depth of aerosol in dust storms and clear days.

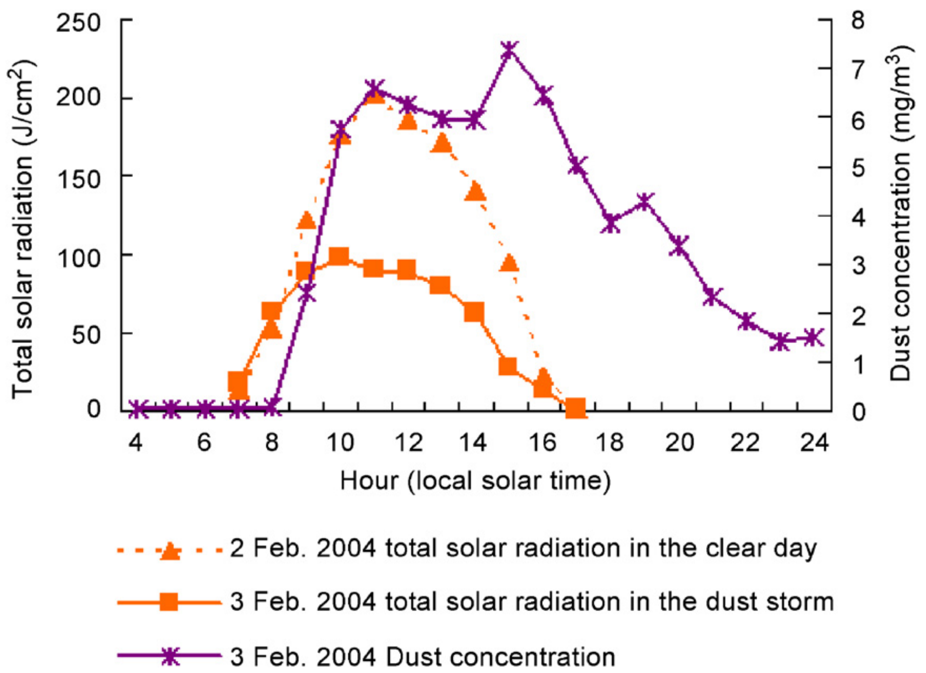

Fig. 7. The inter-daily variation of the total solar radiation under typical weather, under dust and in clear days, and the inter-daily variation of the dust concentration under dust weather.

3.3. The temporal and spatial distribution of the TIIDS in northwest of China

The values of TIIDS were calculated using data from 168 weather stations in northwest China (Fig. 1) and analysis of the temporal and spatial variation of the intensity of dust storms was made over the past 50 years.

The spatial distribution of 5-year average (1955–1959 and 2000–2005) and 10-year average (1960–1969, 1970–1979, 1980–1989, and 1990–1999) of TIIDS from 1955 to 2005 is presented in Fig. 8, which represents the activities of the dust storms in northwest China. The dust storms were active both in Gobi and Taklamakan Desert in 1950s–1980s, the value of TIIDS were high in both the desert and nearby areas. From 1990s to 2000s, the intensity and frequency of dust storms decreased in both deserts. This decrease also appeared in Minqin station (Fig. 3).

4. Discussing the reducing tendency of intensity of dust storms in northwest China

Northwest China is an arid/semi-arid region. Highly erosion prone silty soil has been deposited by dust storms over ages. Deforestation and overgrazing, exacerbated by population increase have caused degradation in the ecosystem resulting in one of the most fragile ecosystem in the world (Chen et al, 2007).

Under the scenarios of climate change, some unstable environmental factors in the region could vary prominently, such as the intensity of dust storms. The change of the factor may reflect the variations of the other related environmental factors.

Shi et al. (2003) found that when the temperature rose in northwest China during the past decades, the depth of melt waters from glacier of Tibetan Plateau was increasing and the fluxes of the river flow from the plateau through Hexi Corridor to deserts were increasing in the past 20 years by 10–20% compared to that in the 1950s–1980s. The areas of the inner lakes also increased, such as HaLa Lake (38°18′N, 97°35′E, 4078 m), an inner lake on Tibetan Plateau, the area of which has increased from 40 km^2 in 1994 to 640 km^2 in 2001. The rise of the quantity of inner rivers and lakes may cause the soil moisture to increase in the arid regions or deserts, and may therefore prevent the dust from blowing.

Zhao and Liu (2004) and Qian et al. (2006) have analyzed the circulation pattern of dust storms. They found that the most prominent circulation pattern for dust storms was a low pressure plus a cold front. In late winter and early spring when cold-dry air from North Mongolia moves to the south, it meets warm and humid air to form cold fronts and low-pressure systems in the middle latitude. The low pressure and the cold front, usually with the ridge over the east of Ural Mountains, could strengthen the ground wind and trigger a dust storm. As the temperature increases, the intensity of the low-pressure system and the strength of the cold front decrease, which may reduce the chance of dust storms or their intensity.

In the past 20 years an increase in temperature can be found in most parts of northwest China and the east of Inner Mongolia, as shown by temperature anomalies using data from 168 weather stations (Fig. 1). Temperature anomalies are defined as follows:

$$\Delta t = (t - \bar{t})$$

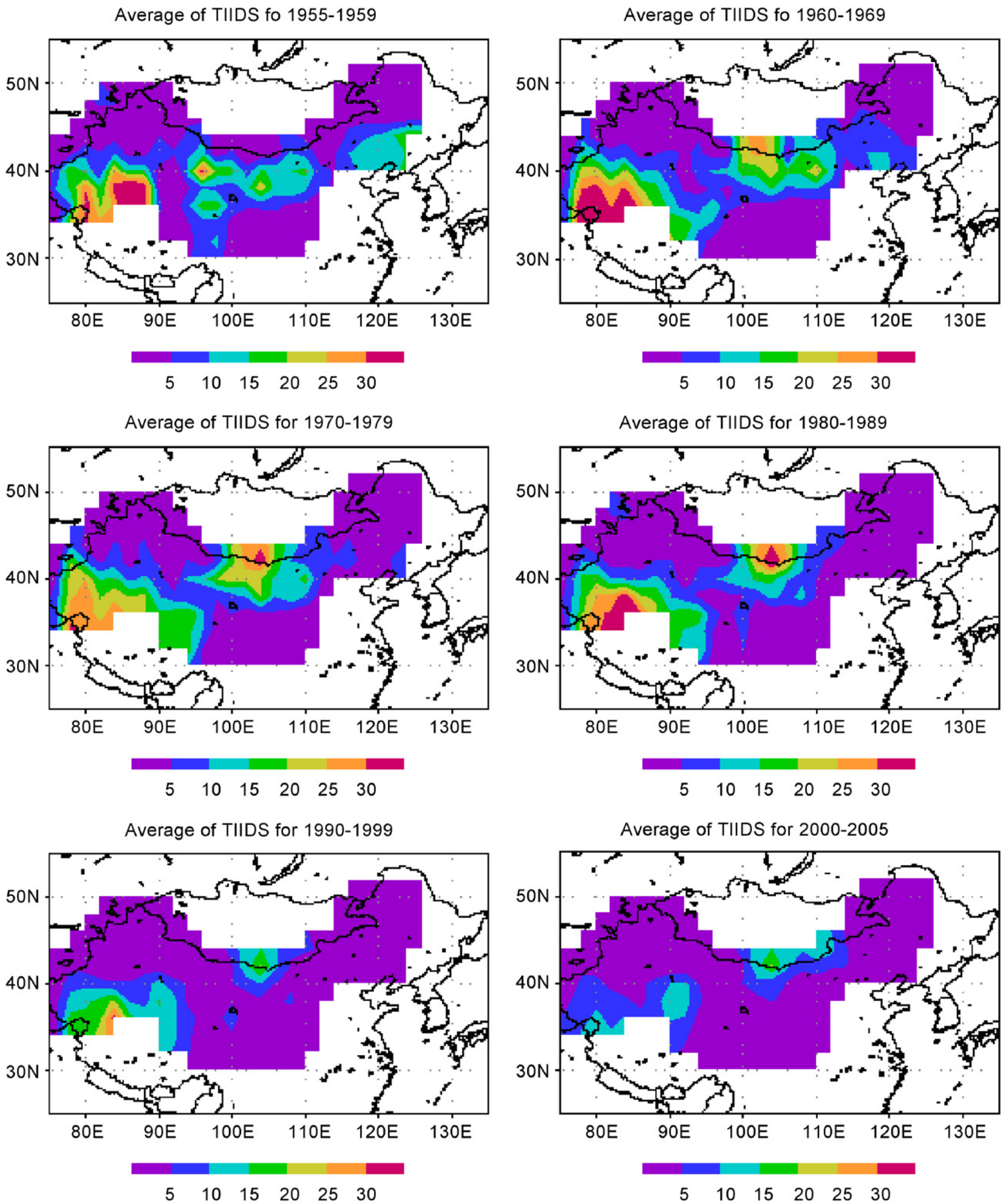

Fig. 8. The spatial distribution of the averaged TIIDS in the northwest China, 1955–1959; 1960–1969; 1970–1979; 1980–1989; 1990–1999; 2000–2005.

where Δt is the temperature anomaly, t is yearly averaged temperature in a weather station, and $\bar{t}$ is 50-year average of t.

The average temperature of Minqin has increased drastically in the past 20 years from 8.0 °C in the middle of 1980s to 9.6 °C in the middle of 2000s, almost 1.6 °C higher (Fig. 10). The increase of temperature in Minqin is during the period much higher than that of the other places of northwest China (average of 0.28 °C/10a in 50 years) and the whole China (0.25 °C/10a in 50 years) (Ren, et al., 2005).

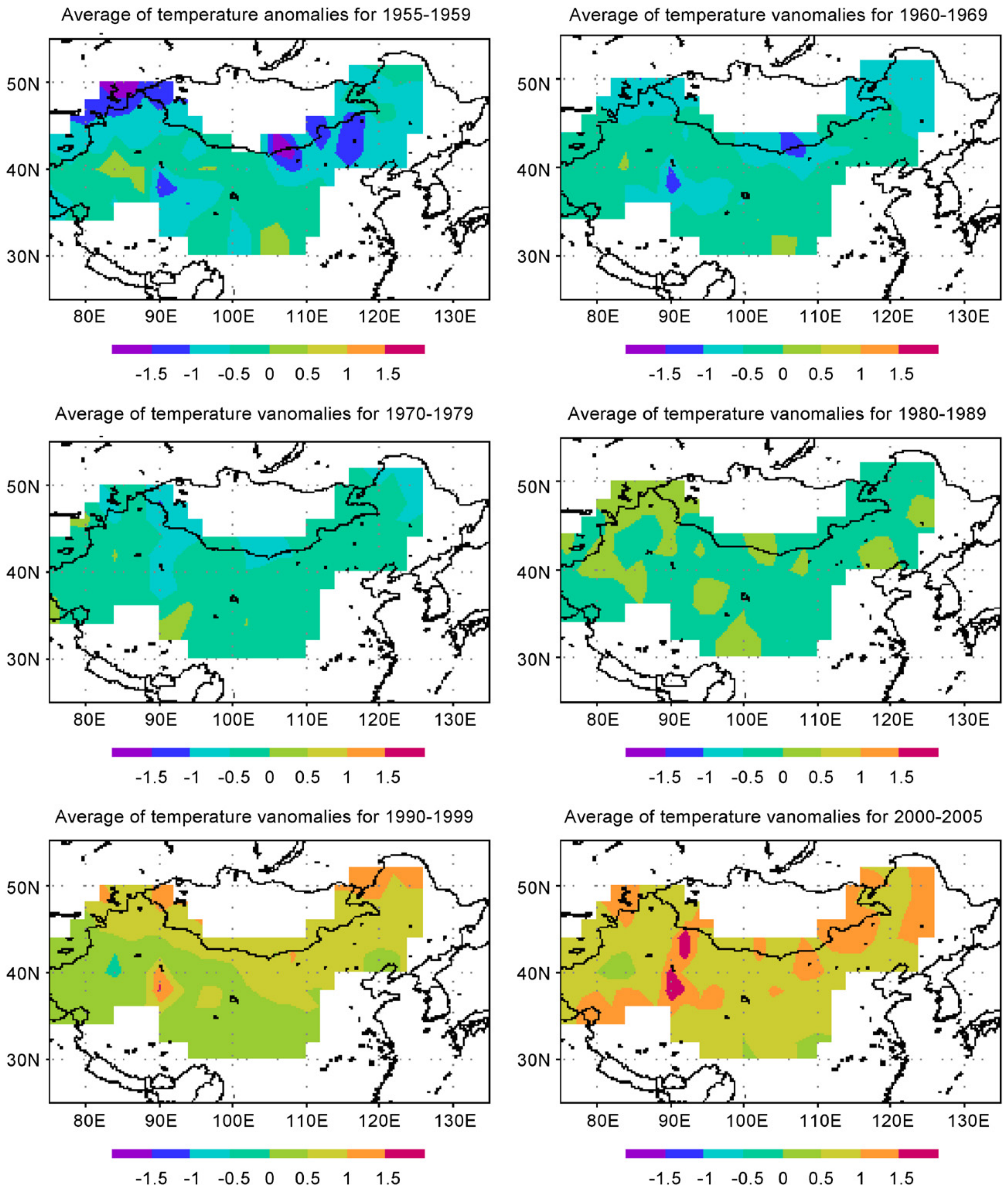

Fig. 9. The same meaning as in Fig. 8 but for the temperature anomalies.

From Figs. 9 and 10, the temperature rise in the past 20 years was prominent in most of northwest China.

The variation of yearly accumulated precipitation in the region during the period varied much; the deviation was about ± 50 mm and there was no consistent trend (Fig. 10). So there is no obvious evidence of more precipitation, which has been suggested as a main factor of reducing dust storms.

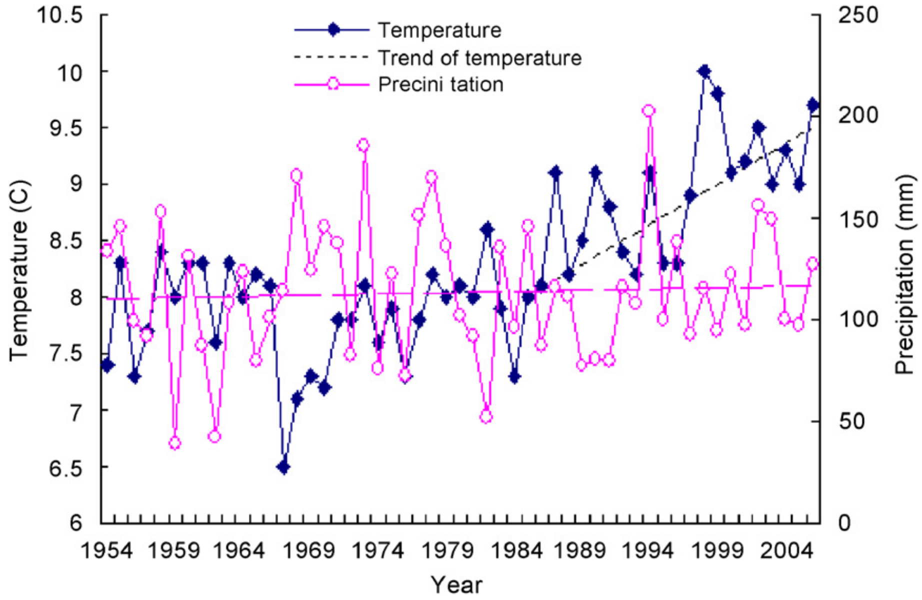

Fig. 10. The temporal variation and the tendency of yearly average of temperature and yearly sum of precipitation in Minqin.

5. Conclusion

Based on the above analysis, we arrive at the following conclusions:

(1) The dust aerosol measured in Minqin weather station: The average of the dust aerosol was about 2.50 mg m^{-3} in dust storms and 0.10 mg m^{-3} in clear days; the averaged optical depth in dust storms was 3.06, almost ten times the value in clear days 0.25; the average visibility in dust storms was 2.08 km, one eighth of that in clear days; the average scatter coefficient of fine particles (PM2.5) were 2385.76 M m^{-1}, >10 times of the value of 209.68 M m^{-1} for clear days.

(2) The trend of the dust storms in the Northwest China: The intensity of dust storms showed a decreasing trend in Minqin and in other northwest regions near deserts from 1990s to 2000s. This trend was correlated with the temperature anomalies in 1990s and 2000s. In the past 10–20 years, the temperature in northwest China was increasing with more anomalies than in the other places. Higher temperature can smooth the intensity of cold flow from the northern Mongolia, which often triggers dust storms.

Acknowledgments

This work was supported by the National Science Foundation of China under Grant no. 40633017. The authors would like to thank the anonymous reviewers for their aid.

References

Breon, F.-M., Tanre, D., Generoso, S., 2002. Aerosol effect on cloud droplet size monitored from satellite. Science 295, 834–838.

Chen, L., Huang, Z., Gong, J., Fu, B., Huang, Y., 2007. The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China. Catena 70, 200–208.

Dockery, D.W., Pope III., C.A., 1994. Acute respiratory effects of particulate air pollution. Annual Review of Public Health 15, 107–132.

Holben, B.N., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setxer, A., Vemte, E., Reagan, J.A., J Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A., 1998. AERONET—a federated instrument network and data archive for aerosol characterization. Remote Sensing of Environment 66, 1–16.

Jigjidsuren, S., Oyuntsetseg, S., 1998. Pastureland utilization problems and ecosystem. In: Ecological Sustainable Development, vol. 2. Ulaanbaatar, pp. 206–212.

Kwon, H.J., Cho, S.H., Chun, Y., Lagarde, F., Pershagen, G., 2002. Effects of the Asian dust events on daily mortality in Seoul, Korea. Environmental Research 90, 1–5.

Menon, S., Del Genio, A.D., Koch, D., Tselioudis, G., 2002. GCM simulations of the aerosol indirect effect: Sensitivity to cloud parameterization and aerosol burden. Journal of Atmospheric Sciences 59, 692–713.

Moria, I., Nishikawaa, M., Tanimurab, T., Quan, H., 2003. Change in size distribution and chemical composition of kosa (Asian dust) aerosol during long-range transport. Atmospheric Environment 37, 4253–4263.

Natsagdorja, L., Jugdera, D., Chung, Y.S., 2003. Analysis of dust storms observed in Mongolia during 1937–1999. Atmospheric Environment 37, 1401–1411.

Ostro, B.D., Hurley, S., Lipsett, M.J., 1999. Air pollution and daily mortality in the Coachella Valley, California: a study of PM10 dominated by coarse particles. Environmental Research 81, 231–238.

Qian, Z.A., Cai, Y., Liu, J.T., Liu, C.M., Li, D.L., Song, M.H., 2006. Some advances in dust storm research over China–Mongolia areas. Chinese Journal of Geophysics 49, 83–92.

Ren, G.Y., Chu, Z.Y., Zhou, Y.Q., Xu, M.Z., Wan, G.Y., Tan, G.L., Zhai, P.M., Shao, X.M., Zang, A.Y., Chen, Z., Guo, J., Liu, H.B., Zhou, J.X., Zhao, Z.C., Zhang, L., Bai, H.Z., Liu, X.F., Tang, H.Y., 2005. Recent progresses in studies of regional temperature changes in China. Chinese Climatic and Environmental Research 10 (4), 701–716.

Shi, N., Yafeng, Yongping Shen, Dongliang Li, Guowei Zhang, Yongjian Ding, Ruji Hu, Ersi Kang, 2003. Discussion on the present climate change from warm-dry to warm-wet in northwest China. Chinese Quaternary Sciences 23, 152–164.

Wang, X., Huang, J., Ji, M., Kaz Higuchi, 2007. Variability of East Asia dust events and their long-term trend. Atmospheric Environment.

Xuan, J., Sokolik, I.N., Hao, J., Guo, F., Mao, H., Yang, G., 2004. Identification and characterization of sources of atmospheric mineral dust in East Asia. Atmospheric Environment 38, 6239–6252.

Ying, I. Tsaia, Chien-Lung, Chenb, 2006. Characterization of Asian dust storm and non-Asian dust storm PM2.5 aerosol in southern Taiwan. Atmospheric Environment 40, 4734–4750.

Zhang, X.Y., 2001. Source distributions, emission, transportation, deposition of Asia dust and loess accumulation. Quaternary Science 21, 29–40 (in Chinese).

Zhao, C.G., Liu, H.Z., 2004. Analysis of circulation situation occurring sand storm in the northern China. Chinese Journal of Applied Meteorological Science 15, 245–250 (in Chinese).