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Wind Erosion and Wind Erosion Research in China: A Review

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Abstract: The past few years have seen an alarming increase in the frequency and intensity of dust storms in Northwest China, which is known to be a major dust source in the world. This outstanding environmental issue is an active research field in China, with the participation of a large number of research groups and scientists from various disciplines. This paper attempts to give an overview of the wind erosion problem in China and to provide a review of the research activities and recent results published in Chinese journals. The review covers four different research areas, including wind erosion climate, monitoring, mechanism and modeling.

Key words: Wind erosion in China, wind erosion climate, wind erosion monitoring, wind erosion modeling, wind erosion mechanism.

Northwest China is one of the major dust sources in the world. The annual precipitation in this region is no more than 400 mm and the driest parts receive less than 30 mm rainfall each year. In late spring and early summer, large quantities of dust particles are lifted from the desert areas by strong surface winds and transported downwind over large distances. Airborne dust particles not only have a dramatic impact on the air quality of regions downwind of the dust sources, but also significantly influence the radiation processes of the atmosphere. In extreme cases, severe dust storms result in the loss of human lives and severe disruption of social and economic activities.

The past few years have seen an alarming increase in the frequency and intensity of dust storms in northwest China. Wind erosion has become one of the most outstanding environmental problems in China, attracting much domestic and international attention. In conjunction with the social, economic and environmental engineering measures being taken in combating the problem, wind erosion has become an active research topic in China, with the participation of a large number of research groups and scientists from various disciplines. In the international arena, scientists from the USA, Japan, Korea and several other countries have initiated research projects on the emission and transport of dust originated from the region.

Wind erosion research in China has a focus on the following five issues:

- *Wind erosion climate*: Effort has been made to establish the climatic features of wind erosion in northwest China, in particular to the statistical evaluation of the spatial and temporal patterns of dust storm activities.

- *Climatic and land-surface conditions for wind erosion*: Previous studies have mostly focused on the atmospheric conditions under which wind erosion occurs (e.g., Ye *et al*., 2000; Dong *et al*., 2000). Many of these studies are qualitative, but there have been several detailed numerical simulations (e.g., Cheng and Ma, 1996). With the development of GIS (Geographic Information System) technology, more attention is being paid to soil and land surface factors. For example, Zhang *et al*. (2001) have obtained and analyzed the spatial distribution of soil, vegetation, wind strength, precipitation and estimated wind erosion index.

- *Wind erosion monitoring using remote sensing*: Remote sensing techniques have been applied to the monitoring of dust storm outbreaks. This approach is potentially a powerful tool for the assessment of large-scale wind erosion activities. Due to technical difficulties, the applications of remote sensing are so far limited to pattern recognition of dust storms and the identification of areas prone to wind erosion (e.g., Fang *et al*., 2001; Qiu and Sun, 1994).

- *Wind erosion mechanism*:Wind tunnel and field experiments have been carried out for studying the mechanisms of wind erosion, especially for establishing the relationships between sand drift intensity and wind velocity for various soil and land-surface types (e.g., Liu, 1999).

- *Wind erosion modeling*: Wind erosion related modeling has been active in China for some time. Most studies are devoted to the simulation of the synoptic and/or meso-scale atmospheric systems (e.g., Cheng and Ma, 1996), or the long-range transport of dust (e.g., Huang and Wang, 1998).

The research carried out by the Chinese scientists has contributed much to increased understanding of wind erosion, especially wind erosion in northwest China, but unfortunately their results are mostly published in Chinese language, and are often not readily assessable. The objectives of this paper are to give an overview of the wind erosion problem in China and to provide a review of the related research activities and results published in Chinese journals. In the concluding remarks, we summarize the problems of past research and discuss the future research needs.

Wind Erosion in China

Arid and semi-arid areas occupy 37.2% of China, covering 3.57 million km^2 (Ci and Wu, 1997), consisting of 0.253, 1.427, 1.139 and 0.751 million km^2 area under hyper-arid, arid, semi-arid and dry sub-humid lands, respectively. In these vast regions, wind erosion can be sometimes very severe. However, the exact source regions of individual dust storms are not well known, although the techniques for remote sensing and the networks for meteorological observations are nowadays much improved.

In China, there is not yet a unified definition of wind erosion events. In practice, such events are often classified as *Fu Chen* (dust in suspension), *Yang Sha* (blowing sand) and *Sha Chen Bao* (dust storm) according to observed horizontal visibility. A more detailed description of the three classes is as follows:

- *Dust in suspension*: Under moderate wind conditions, dust particles lifted from upwind source regions remain suspended

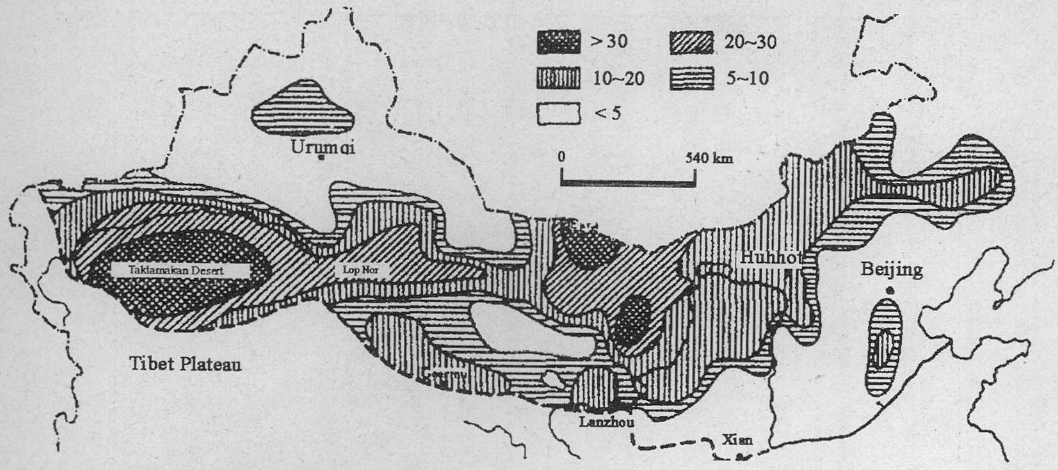


Fig. 1. Spatial distribution of dust-storm frequencies in China (Dong et al., 2000).

in the atmosphere and the horizontal visibility is less than 10 km;

- *Blowing sand*: Under strong wind conditions, a considerable amount of soil particles is lifted from the surface, reducing the visibility to 1 to 10 km;
- *Dust storm*: Very strong winds lift large quantities of soil particles, reducing the horizontal visibility to less than 1 km. In extreme cases, visibility can be reduced to 0.

Spatial pattern

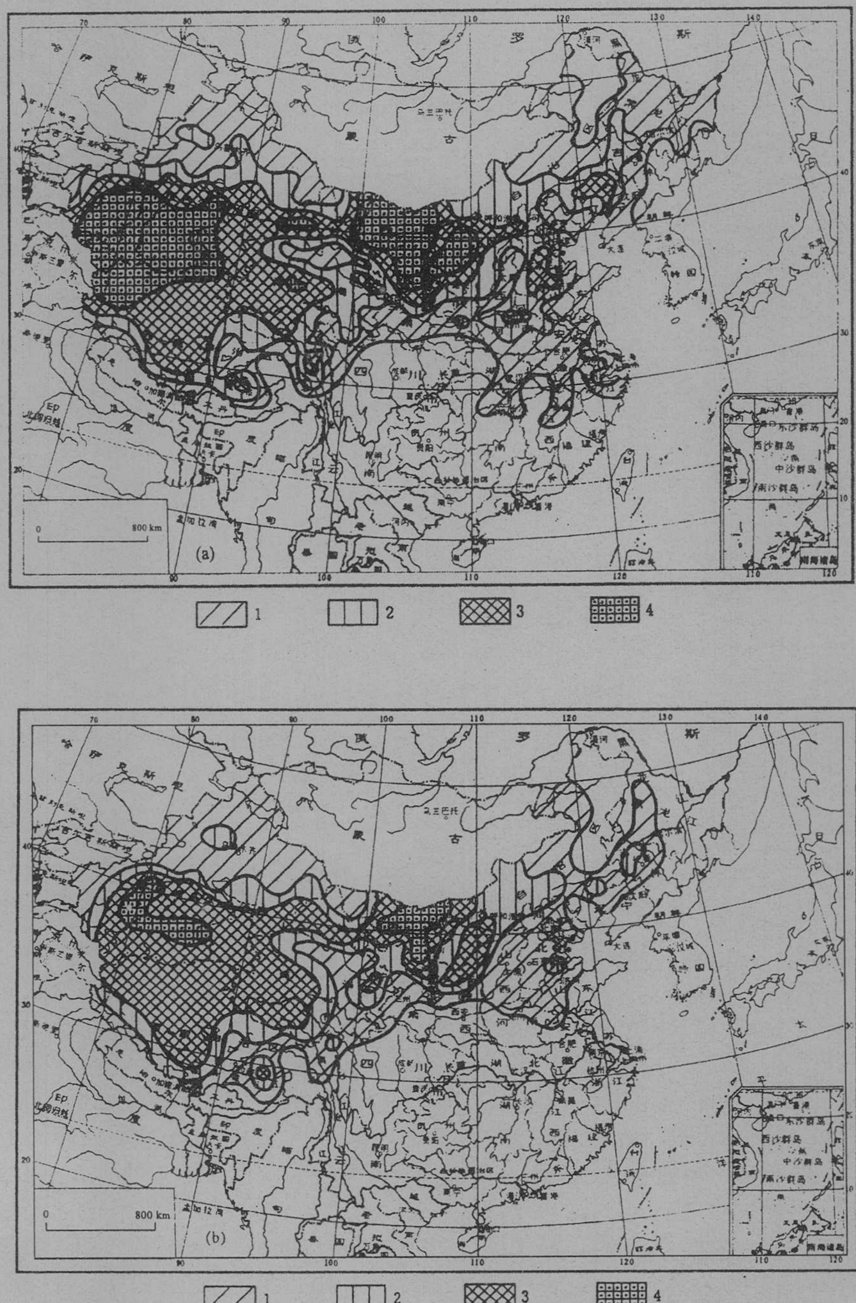
Figure 1 shows the spatial distribution of dust storm frequencies in China. Five areas with frequent dust storms are identified. These are, in sequence from west to east:

- Tarim Basin: including Taklamakan Desert and the Lop Nor area;
- Alashan Plateau: including Badain Jaran Desert, Tengger Desert, Ulan Buh Desert and Hexi Corridor (Hexi refers to the adjacent areas to the west of the Yellow River);
- Ordos Plateau: including Mu Us Sandy Land and the northern Loess Plateau;
- Southeastern Inner Mongolia Plateau: including the Houshan area, Otingdas Sandy Land and Horqin Sandy Land; and the
- North China Plain.

Based on meteorological observations over a period of forty years, Shi *et al.* (2000) identified three regions of frequent dust storms, which are not inconsistent with the findings of Dong *et al.* (2000).

The most reliable assessment of wind erosion pattern in China is probably that of Zhou (2001) who carried out a comprehensive investigation of wind erosion events using the original meteorological records of 681 weather stations over a period of 40 years (1959-1998). Zhou (2001)

(a)



(b)

Fig. 2. Patterns of blowing sand events (a) and dust storms (b) in China for the period of 40 years between 1959 and 1998 (Zhou, 2001).

Table 1. Classification of different wind erosion regions according to the annual total number of dusty days (from Zhou 2001)

Class	1	2	3	4
Days of blowing sand	1 to 10	10 to 20	20 to 40	>40
Days of dust storms	1 to 5	5 to 10	10 to 20	>20

separated blowing sand events from dust storms and classified wind erosion regions into four categories according to the total number of dusty days (Table 1). The results of Zhou (2001) are presented in Fig. 2 that reveals two most active centers of wind erosion. The first one includes the Tarim Basin and adjacent areas and the second one includes the Alashan region, the Ordos region and the Hexi Corridor region. The analysis revealed that in some locations, the annually averaged number of days of blowing dust can exceed 80, e.g., 101 for Jinantai (Inner Mongolia), 88 for Yanchi (Ningxia), 93 for Pishan and 82 for Minfong (both in Xingjiang). The annual total number of days with dust storm can exceed 30, e.g., 36 for Minfong (Xingjinag), 32 for Keping and 30 for Minqin (both in Gansu). The classes for blowing sand and dust storm events are given in Table 1.

Temporal evolution

Wind erosion as a geological and climatological process has been active in northwest China for many years. The frequency and intensity of wind erosion activities undergo clear variation on seasonal,

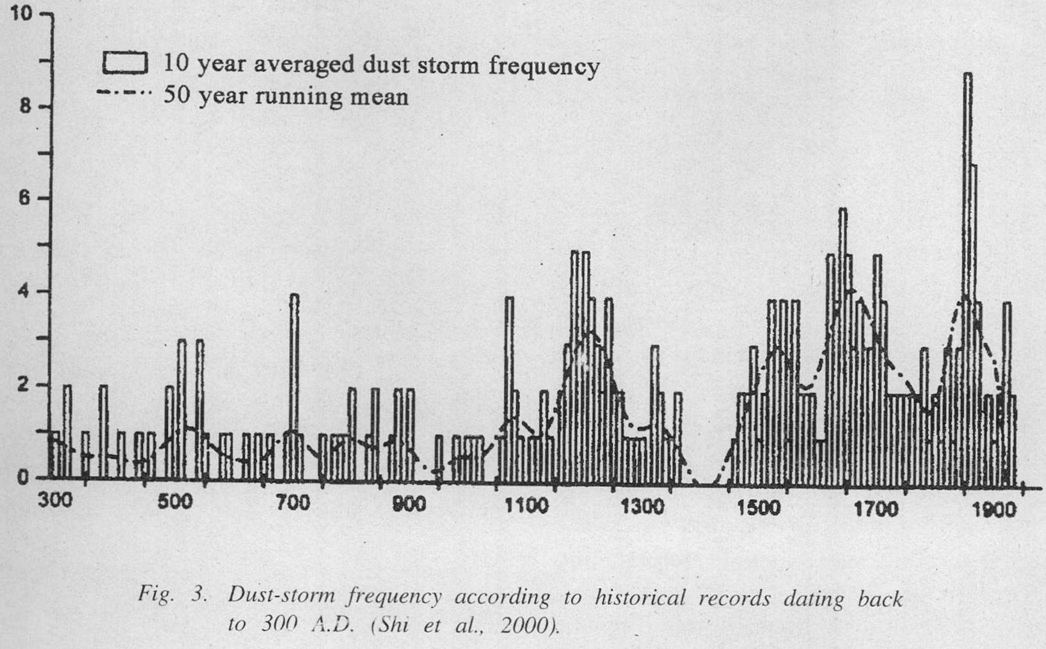


Fig. 3. Dust-storm frequency according to historical records dating back to 300 A.D. (Shi et al., 2000).

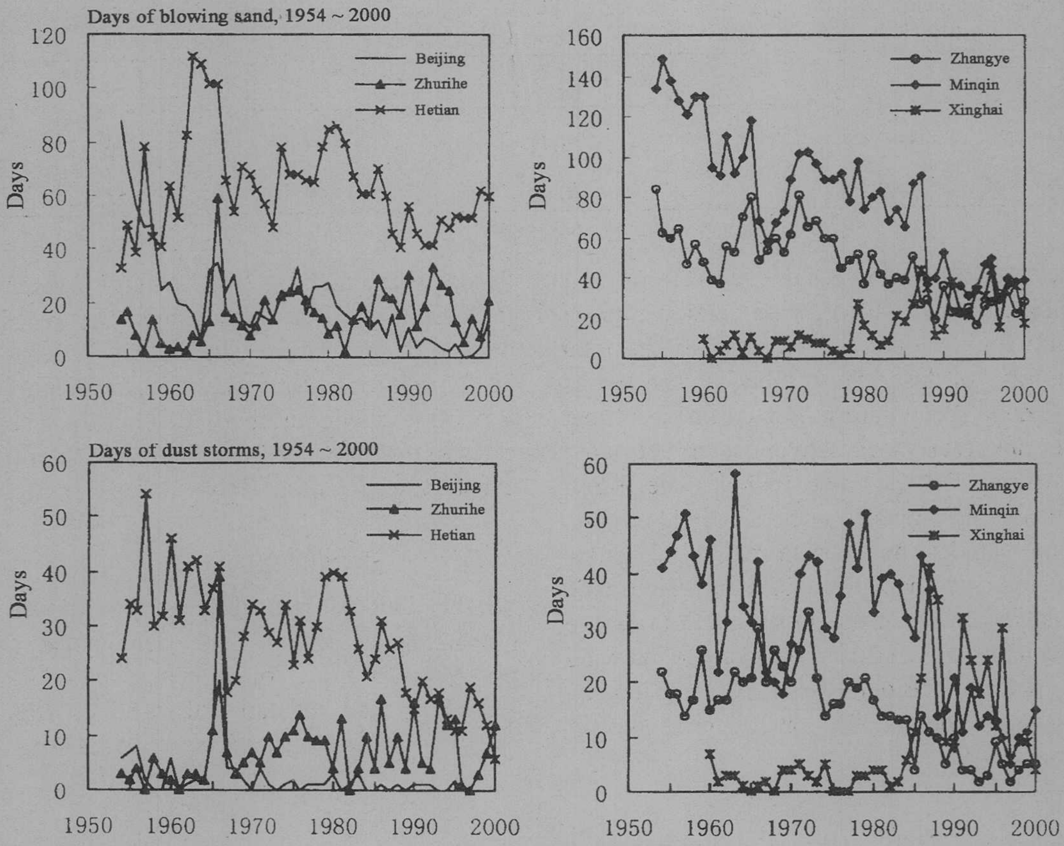


Fig. 4. Annual number of blowing-sand and dust-storm days for six representative stations: Beijing, Zhurihe, Hetian, Zhangye, Minqin and Xinghai for the period between 1954 and 2000 (Zhou, 2000).

annual, decadal or even longer time scales. The long-term impacts of wind erosion on the landscape are evident from the yardangs sculptured by wind and the deflated Gobi deserts. Documentation of wind erosion and dust storms in China dates back to over 2000 years. The expressions of 'Earthy Rain' and 'Sandy Rain' in history books refer to the rain-laden dust resulting from wind erosion. Richthofen (1882) attributed the thick loess deposition to wind erosion taking place in the sandy and Gobi deserts upwind. Hedin (1905) noted that in the previous 1600 years, the yardangs near Lop Nor had been eroded 6 meters by wind. The estimated erosion rate was 4 mm y^{-1} or 6000 tonnes km^{-2} y^{-1}.

Figure 3 shows the dust storm frequency according to historical records dating back to 300 A.D. Around 1100 A.D. there was a sharp increase in dust storm frequencies. Between 1000 AD and 1900 AD there were 5 periods of frequent dust storms: 1060-1090, 1160-1270, 1470-1560, 1610-1700 and 1820-1890. These records

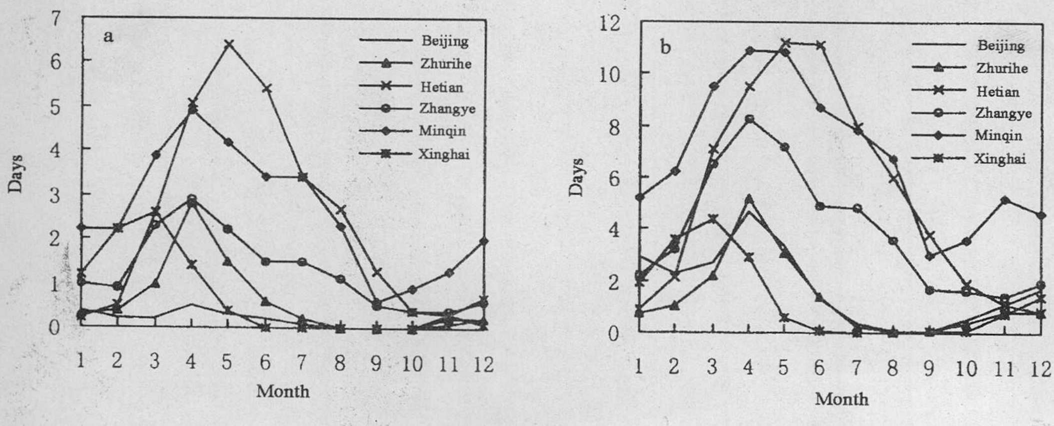


Fig. 5. Seasonal variation of blowing-sand events (a) and dust storms (b) for 6 representative stations, including Beijing, Zhurihe, Hetian, Zhangye, Minqin and Xinghai, for the period between 1954 and 1998 (Zhou, 2000).

are consistent with the records of ice-cores collected in the Honan mountains.

Qiu *et al.* (2001) analyzed daily surface weather maps and meteorological observations for the period between 1971 and 1996 (1993 and 1994 are missing) and identified 4147 dust-storm events in the 24-year period. The record shows that the number of dust storms is generally in decline for that period. In particular, there was a marked decline in the number of dust storms after 1984. Zhou (2000) selected 6 representative stations and examined the annual occurrence of blowing sand and dust storms for the period between 1954 and 2000. The results are shown in Fig. 4. Zhou (2000) also concluded that the annual numbers of blowing sand and dust storms are generally on the decline in northwest China, and is agreement with the analysis of Qiu *et al.* (2001).

Wind erosion in China shows clear seasonal variations. This is best seen from the monthly averaged number of blowing sand events and dust storms of six representative stations in northwest China (Fig. 5). In some stations, such as Minqin, wind erosion may be active in all seasons, but there is a general tendency that wind erosion is markedly weaker in the second half of the year. While the situation varies from station to station, blowing sand events and dust storms are most active in months of March to June.

Severe dust storms

Some of the most severe dust storms were observed in recent years. For instance, on the 5th May, 1993, dust storm occurred in the areas of Xingjiang, Turpan, Hami, Gansu, Hexi, Ningxia and Inner Mongolia, resulting in the loss of 85 human lives, 264 injuries and the loss of 120,000 animals. Another 264 people were reported missing. The depth of the eroded surface soil layer was estimated to be between 100 and 300 mm and the observed dust deposition in some areas amounted to 161 to 256 t km^{-2}. The dust storm also resulted in damages

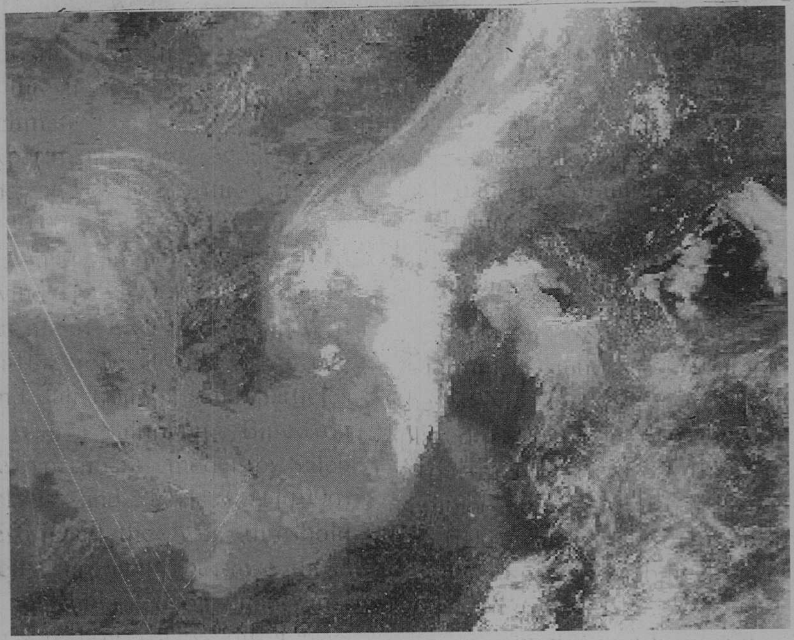


Fig. 6. Satellite image of the dust storm originating in the Takla Makan desert of northwest China on 14 April, 1998. The image, from 16 April 1998, shows the dust clouds behind the cold front and near the center of the storm (SeaWiFS image produced by Norman

to 0.373 million km^2 crop land, 1000 water channels, 6012 power lines and 4412 houses. A major railway track (Lanzhou to Xingjiang) was interrupted for 37 hours. The total economic damage amounted to 5600 million RMB. A similar severe dust storm occurred during April 14-16, 1998, affecting 1560,000 people. This dust storm resulted in the loss of 110,000 animals and an economic damage of 8000 million RMB. Figure 6 shows the satellite image of the dust storm originating in the Takla Makan desert of northwest China on 14 April, 1998. The image was for 16 April, 1998.

Climate and Land-surface Conditions

Wind erosion activities in northwest China are closely related to the climate conditions and land-surface properties in the region. It is the consequence of a combination of four major factors, i.e.,

- lack of precipitation;
- lack of vegetation cover;
- mobile sandy soil; and
- strong winds.

Recent studies carried out by Chinese researchers have provided a reasonably adequate assessment of the spatial distribution and temporal evolution of wind erosion in China, as described in the previous section. In addition, numerous case studies have been carried out on the climate and weather conditions for major dust storm events. In the past few years, increased attention has been paid to the responsible land-surface properties.

Table 2. Monthly and annual rainfall of representative stations of northwest China for 1951-1980 (adapted from Wang et al., 1995)

Station	1	2	3	4	5	6	7	8	9	10	11	12	Total	Winter season %
Bazu	0.8	1.6	0.2	2.3	5.6	9.9	11.2	8.4	2.7	1.3	0.4	0.4	43.3	10.8
Pishan	0.4	4.6	2.5	2.6	12.7	5.6	6.4	3.7	5.9	2.2	0.6	0.6	48.2	23.4
Hetian	1.5	2.8	0.8	2.8	6.8	7.0	3.8	3.4	2.9	0.6	0.4	0.7	33.4	20.4
Minfong	1.1	1.4	0.6	1.7	6.0	5.7	7.7	2.7	2.2	0.1	0.1	0.5	29.9	12.7
Denghuang	0.8	1.6	1.2	2.9	1.6	6.7	12.1	5.3	1.8	1.0	1.1	0.7	36.8	17.4
Jioquan	1.6	2.4	3.0	5.3	9.1	10.7	20.6	17.1	10.5	1.8	1.9	1.3	85.3	14.1
Zhangyie	1.8	1.3	3.2	4.8	13.0	19.3	27.7	30.9	18.0	5.0	2.4	1.6	129.0	11.9
Minqin	0.7	0.5	2.5	4.7	8.3	12.3	20.3	36.9	18.6	7.6	2.2	0.4	115.0	12.1
Zhonglin	1.0	1.2	3.8—	11.7					6.2	14.9	4.8	0.9	222.7	11.9
Jilantai	0.9	1.0	1.6	5.8	5.9	13.4	28.7	37.6	13.0	5.8	2.3	0.1	116.0	10.1

Rainfall: Northwest China is an arid to semi-arid region with very low precipitation. In general, wind erosion is confined to an area with annual rainfall less than 400 mm. Some of the inland areas can be extremely dry. For example, the annual precipitation for the southern part of Xingjing can be as low as 20 mm, e.g., Noqian's precipitation is 17.4 mm based on the observations for the period between 1951 and 1980. The annual rainfall of Hetian is 33 mm. Table 2 gives a summary of annual precipitation of nine representative stations. In these areas, rainfall is concentrated in summer with 77% of the total rain falling between June and September and 23% during rest of the seasons. Hence, northwest China is mostly extremely dry. Zhang *et al.* (2001) further calculated the distribution of soil surface dryness for China. According to them the soil surface dryness, D, is defined as

$$D = 0.16\ (T10C)/P$$

where,
(T10C) is the annual cumulative temperature above 10°C and P is annual precipitation. The surface dryness calculated in this way (Fig. 7) indicates that large areas in northwest China are very dry, which is as expected.

Circulation: Wind erosion activity in northwest China is closely associated with intense frontal systems. As an example, the system that generated the May 1993 dust storm is depicted in Figs. 8-10. This severe dust storm occurred on 5 May, 1993 and swept through Turpan and Hami of Xingjing, Gansu to the west of the Yellow River, Ningxia and Inner Mongolia.

The mechanism leading to the development of the particularly intense frontal system is a combination of large-scale circulation pattern and topographical

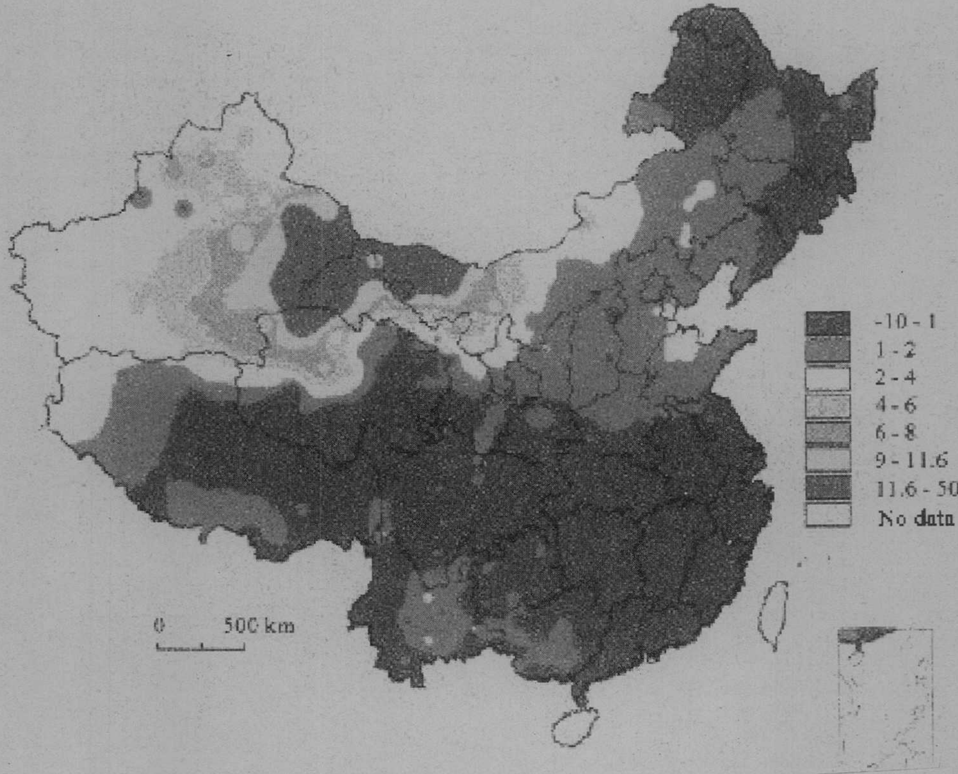


Fig. 7. Distribution of land surface dryness for China (Zhang et al., 2001).

effects. The analysis of the synoptic situation reveals that on 2 May, 1993, cold air was gathering strength in north Siberia with the temperature at the cold center being as low as -40°C. The trough was located near Omsk in West Siberian Plain. As the trough deepened, the northwesterly wind behind the trough increased. By 5 May, 1993, a cutoff low was developing, accompanied by a cold air burst towards southeast (Fig. 8). The blockage of the Altai and Tian Mountains generated a channel effect that strongly accelerated the near-surface wind. At the same time, the adiabatic heating from the Tibet Plateau to the south strengthened the north-south temperature contrast, which also affected the flow speed. Under these synoptic and topographic conditions, the near-surface wind speed for this event reached as high as 35 m s^{-1}. The surface synoptic situation is illustrated in Fig. 9. Variation of near-surface atmospheric quantities, including air temperature (T), pressure (p), wind speed (V), and relative humidity (r), at the passage of the cold front for the 5 May, 1993 dust storm is presented in Fig. 10. The quantities were observed at Jinchnag station (Cheng and Ma, 1996). As can be seen, temperature, pressure, wind

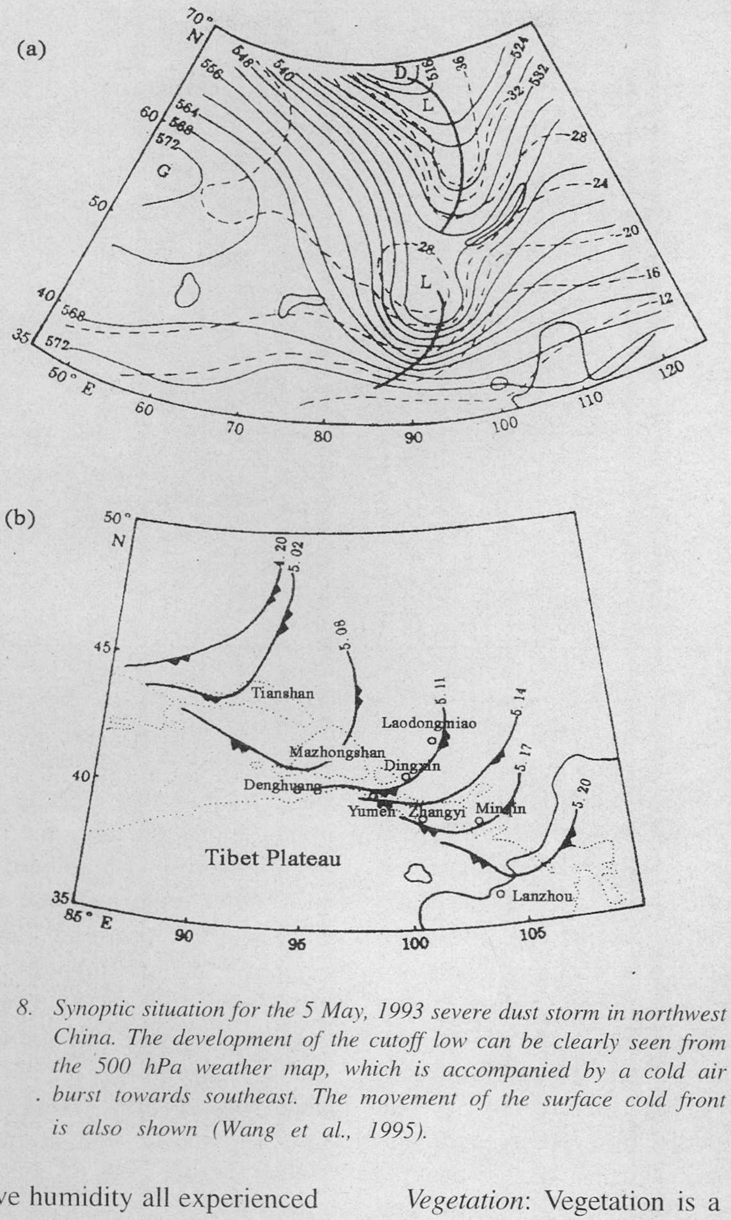


Fig. 8. Synoptic situation for the 5 May, 1993 severe dust storm in northwest China. The development of the cutoff low can be clearly seen from the 500 hPa weather map, which is accompanied by a cold air burst towards southeast. The movement of the surface cold front is also shown (Wang et al., 1995).

speed and relative humidity all experienced dramatic changes at the cold front, which demonstrated features of a squall line. More detailed analysis can be found in Cheng and Ma (1996) who used a limited area atmospheric model and simulated the structure of this intense system.

Vegetation: Vegetation is a major factor influencing wind erosion. The low precipitation in the arid and semi-arid regions of China is accompanied by the lack of vegetation cover and consequently, the surfaces in these regions have low threshold friction velocity and are, therefore, exposed

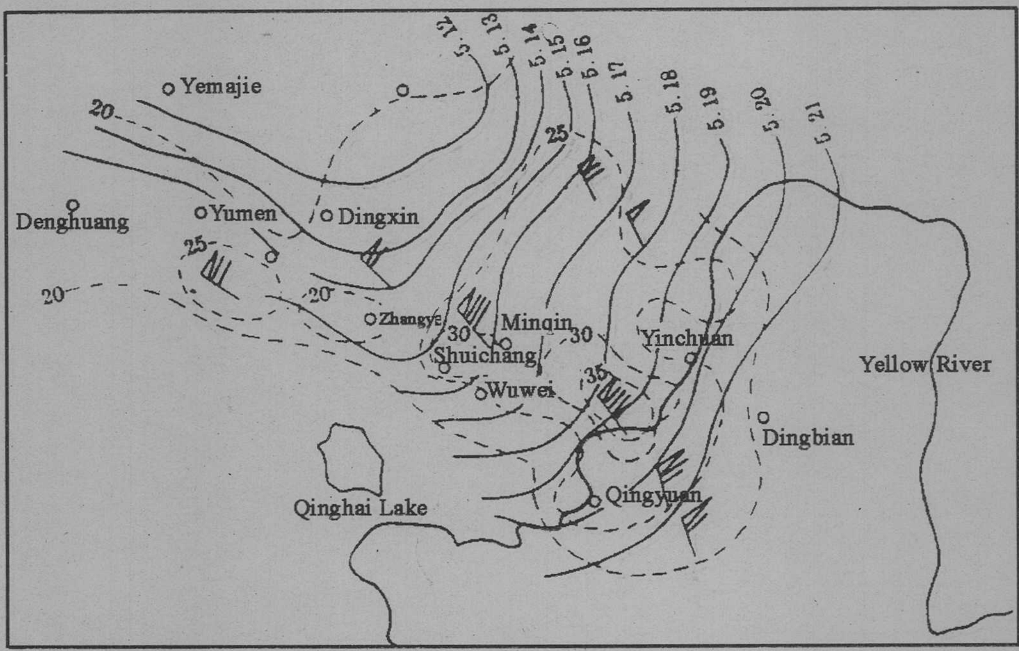


Fig. 9. Synoptic situation (surface weather) map for the 5 May, 1993, severe dust storm (Wang et al., 1995).

to erosion. Leaf-area index is an indicator commonly used for vegetation cover. For large areas, this value can be derived empirically on the basis of NDVI which is defined as NDVI = ch2-ch1/(ch2+ch1), using NOAA satellite data. In the above expression, ch1 and ch2 represent the reflective radiation in the red region (0.55-0.68 micron) and the near-infrared region (0.72-1.1 micron) of the electro-magnetic spectrum, observed through channel 1 and channel 2 of the satellite sensor. Figure 11 shows the NDVI data for China and the surrounding areas. Large areas in northwest China have very little vegetation cover.

Soil: Figure 12 shows the distribution of soil types in China. Most soils with high clay content are distributed in the eastern part of China that are affected by the East Asian monsoon, and in limited areas in southwestern and northeastern China. Soils in the desert regions are predominantly sandy. Silty soils are mostly distributed in arid and semi-arid regions in northwest China and the Gobi. This distribution of soil types suggests that soils in the arid and semi-arid regions are intrinsically mobile. The approximate particle size distributions for three typical soils in northwest China are shown in Table 3.

Niu *et al.* (2001) carried out an investigation on ambient dust concentrations and particle size distributions in the Helan mountainous region adjacent to the Badain Jaran Desert, Tengger Desert and Mu Us Sandy Desert. They collected a large number of ambient samples (at heights between 1

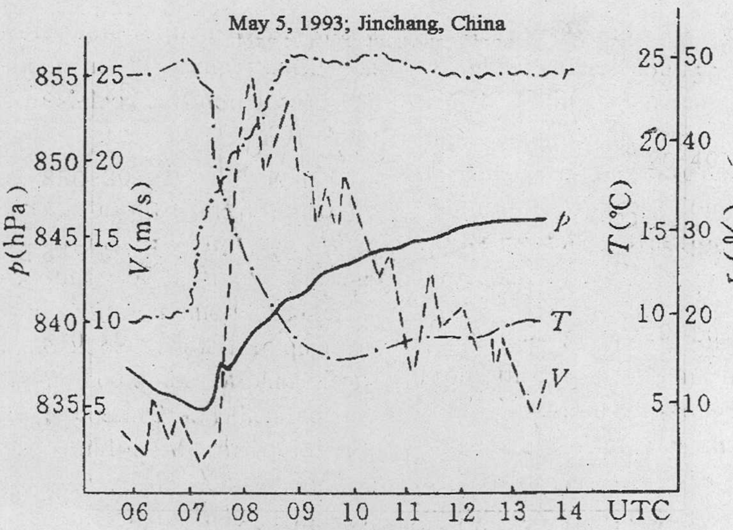


Fig. 10. Variation of near-surface atmospheric quantities, including air temperature (T), pressure (p), wind speed (V), and relative humidity (r) at the passage of the cold front for the 5 May, 1993, dust storm. The quantities were observed at Jinchnag station (Cheng and Ma, 1996).

and 4 meters) in April and May between 1996 and 1999, and analyzed these samples using APS-3310A. Their results are summarized in Table 4. It is revealed that the background dust concentration is around 0.1 mg m^{-3} on average, while it increases to about 1.14 mg m^{-3} during dust storm situations. The typical particle size of ambient dust is around 1 micron. Figure 13 shows the ambient dust particle size distribution for background, dust in suspension, blowing sand and dust storm events. It is shown that the peak particle size values for all these events are around 1 to 2 microns and most of the particles are smaller than 10 microns. Compared to the background case, the typical particle size is somewhat larger. The study of Niu *et al*. (2001) suggests that dust particles emitted from northwest China are mostly very fine.

Wind-erosion Modeling

Wind erosion modeling has been active in China for some time. Earlier studies were mostly devoted to the simulation of the synoptic and/or meso-scale atmospheric systems (e.g., Cheng and Ma, 1996) or the long-range transport of dust (e.g., Huang and Wang, 1998). The study of Huang and Wang is probably the most detailed wind erosion simulation carried out so far in China. These authors designed a simple sand entrainment model and considered to some extent the transport and deposition mechanisms. Huang and Wang also used the analyzed atmospheric data of the ECMWF for driving the wind erosion model and simulated the 9-23 April, 1988 dust storm. The simulated near-surface yellow-sand concentration is in reasonable qualitative agreement with the corresponding

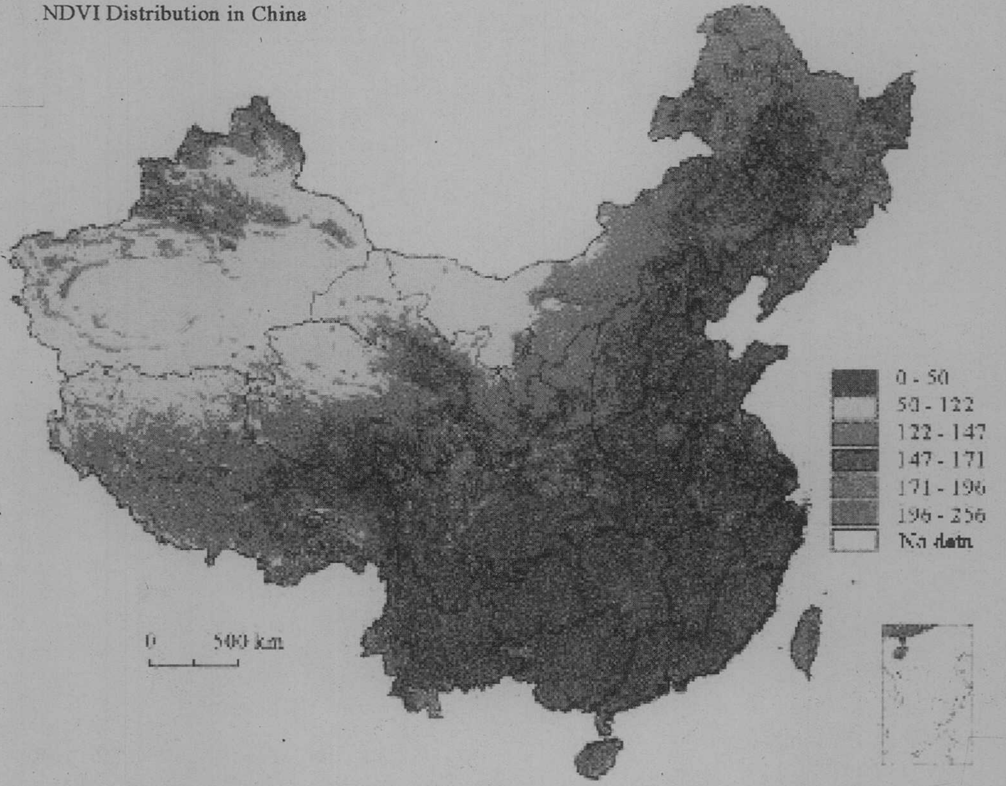


Fig. 11. NDVI distribution in China. Large areas of northwest China have little vegetation cover (Zhang et al., 2001).

meteorological observations. While the study of Huang and Wang (1998) obtained encouraging results, many aspects of the simulation remained rather simplistic, especially in the module for sand and dust entrainment and the use of land surface and atmospheric data. Since 2001, intensive research development is being carried out in a joint project between the Institute of Atmospheric Physics, the Institute of Geography (both the Chinese Academy of Sciences) and the National Satellite Meteorology Center (China Meteorological Administration) to develop a comprehensively

Table 3. Approximate particle size distribution for three typical soils in northwest China

	>2 (mm)	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	<0.05
Sandy loam	5.61	5.15	6.80	6.95	20.52	29.54	25.43
Loamy sand	6.84	7.06	20.13	25.66	25.51	9.79	5.01
Sand dunes	3.11	2.58	2.39	9.13	66.87	11.76	4.16

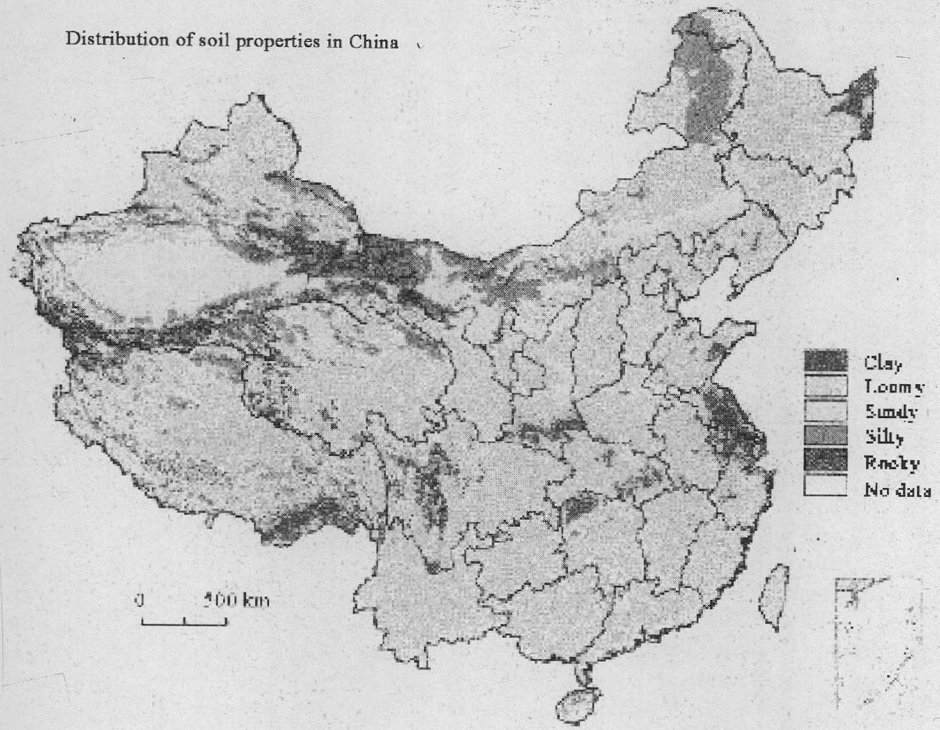


Fig. 12. Distribution of soil types in China (Zhang et al., 2001).

integrated wind-erosion modeling system. In 2002, the integrated system was applied for routine real-time (24, 48 and 72 h) predictions of dust storms for March, April and May. The system is nested in the T213 Global Circulation Model of the China Meteorological Administration. The area of simulation is (30°E, 5°N) to (180°E, 65°N) and the spatial resolution is 50 km. The area of data analysis is (72°E, 15°N) to (148°E, 53°N). The integrated system predicts a number of variables for the quantification of the entire dust cycle, including dust entrainment, transport and deposition. The numerical predictions are compared with meteorological records and satellite images. Figure 14 shows such a comparison for the 7 April, 2002 dust storm. The dots represent the stations where dust storms were observed and the enclosed red curve represents the dust area identified from remote sensing. The quantitative agreement between the prediction and observation is very good.

Remote Sensing

Remote sensing techniques have been recently employed in monitoring the development of severe dust storms. The data sources for this type of work are either polar orbital and/or geostationary satellites. These satellites carry sensors for measuring

Table 4. Statistics of ambient particle samples and analysis for the Helan region (Niu et al., 2001)

Date	Time	No. of samples	Class	Umax ($m\ s^{-1}$)	Dave (μm)	Dpeak (μm)	Dmed (μm)	No. of Dpeak particles	Cave (No. cm^{-3})	Cave (mg m^{-3})
Jilantai										
96-4-23	03:57-18:30	102	BS	11.3	1.5	1.0	1.2	15.5	227	0.94
Yanchi										
98-4-22	09:00-21:32	90	DS	10.8	1.2	1.8	0.9	18.3	288	0.78
98-4-23	06:42-09:42	316	DS	13.1	1.3	0.9	1.1	10.5	185	0.66
98-4-25	09:36-10:33	102	BS	8.7	1.5	0.9	1.1	5.1	101	0.43
98-4-27	03:18-09:21	552	DS	7.8	1.6	1.3	1.3	9.1	186	1.01
98-4-28	07:08-09:31	250	SD	4.2	1.3	0.8	1.0	8.3	140	0.51
98-4-28	09:56-11:20	152	BS	12.1	1.4	0.9	1.1	6.1	114	0.45
98-5-01	14:21-18:10	400	YS	12.1	1.4	1.0	1.1	3.7	62	0.26
98-5-05	10:21-19:52	561	YS	14.2	1.7	1.2	1.4	2.6	48	0.22
Yinchuan										
98-5-19	23:53-00:49	100	SD	3.7	1.6	1.1	1.3	2.6	35	0.12
98-5-27	06:54-19:23	369	BG	14.0	1.5	1.0	1.2	1.2	15	0.05
Alashan Zuo Qi										
99-4-10	12:11-12:20	3	DS	8.0	1.7	1.3	1.4	16.3	28.4	2.10
Bayinho										
99-4-11	12:26-12:28	6	BG	0.7	1.4	1.0	1.4	1.7	27	0.14
99-5-11	09:18-14:03	299	YS	15.0	1.6	1.0	1.2	1.4	31	0.21
99-4-28	10:06-16:18	300	BG	4.0	1.4	0.9	1.1	1.3	26	0.11
			BG		1.4	1.0	1.2	1.4	23	0.10
					1.4	1.0	1.2	5.4	88	0.32
					1.5	1.0	1.2	5.7	97	0.42
					1.5	1.3	1.2	13.5	236	1.14

radiation quantities of various surfaces of the Earth system, including land, ocean, ice-snow, cloud and vegetation surfaces. The spectral channels are commonly set in correspondence with the atmospheric radiation windows. Table 5 summarizes the technique parameters for the AVHRR-3 and the VISSR carried by NOAA satellites.

It is a particularly important and difficult task to identify dust clouds over land surface and to quantitatively determine dust concentration through remotely sensed

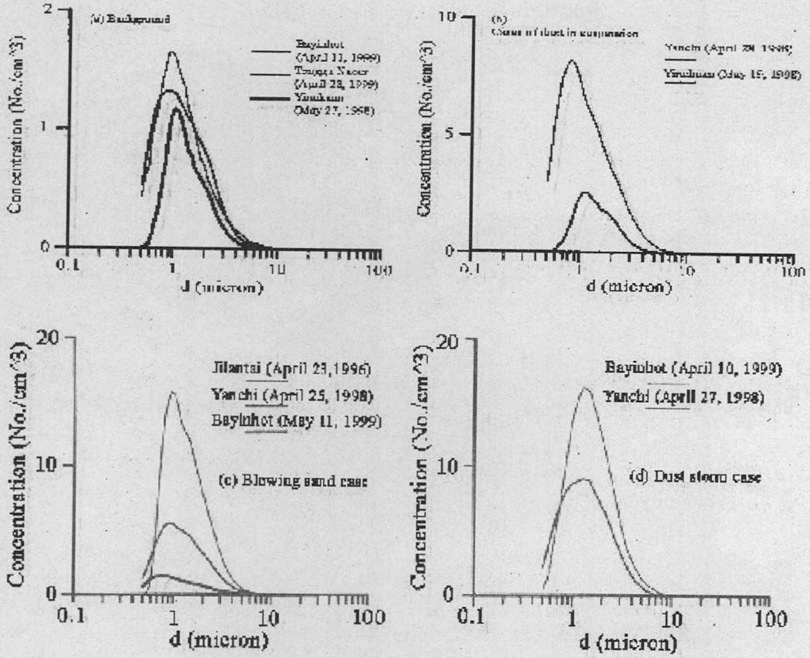


Fig. 13. Particle size distribution for background (a), dust in suspension (b), blowing sand (c) and dust storm (d) events for the Helan mountainous region.

radiation signals. Fang *et al.* (2001) discussed the basic ideas behind the monitoring of dust storms using a combination of the signals obtained through the visible-light and infrared channels of the satellite sensors. Because suspended dust particles are much larger than air molecules, but somewhat smaller than cloud droplets, the radiation effect of dust particles should fall between the Rayleigh diffusion and the Mie scattering. Fang *et al.* (2001) suggested using the difference between ch. 3 and 4 signals for identifying dust clouds. Figure 15 shows a comparison of two NOAA AVHRR satellite images for the 6 April, 2000, dust storm. As can be seen, using this technique Fang *et al.* (2001) have been able to successfully identify the region of high dust concentration. This region stretches along direction from Inner Mongolia to Beijing, with a northwest-southeast width ranging between 500 and 800 km.

Concluding Remarks

Wind erosion in northwest China is an environmental problem of global importance. Dust particles emitted from this region not only have serious consequences on the air quality of the populous regions downwind, but also play an important role in the global aerosol cycle. The recent frequent and severe dust storms have highlighted the need for improved understanding of the problem and the need for effective wind erosion prevention measures. In this paper, we have summarized

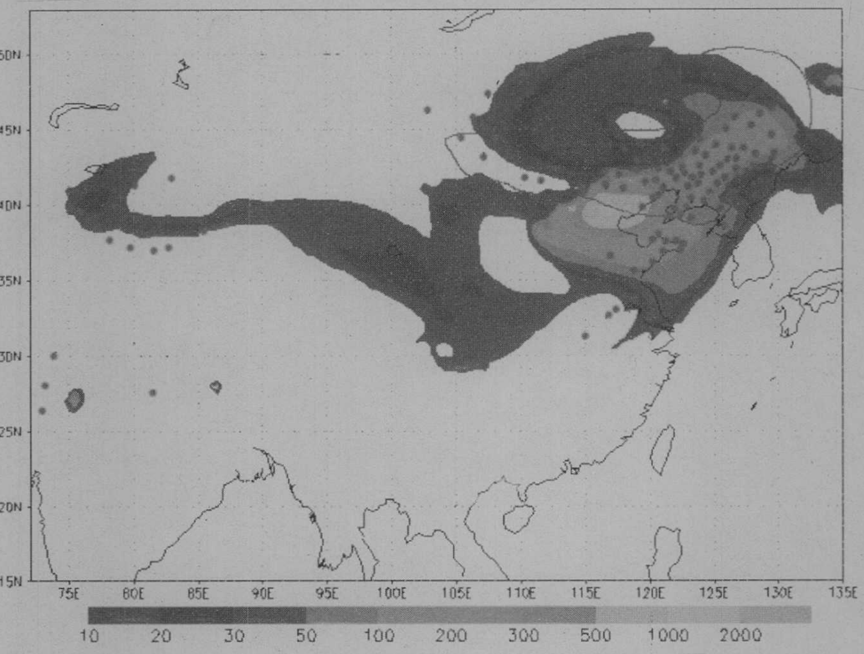


Fig. 14. Simulated near-surface dust concentration in μg m^{-3}, for 7 April, 2002. For comparison, surface meteorological and satellite observations are also shown. The dots represent the stations where dust storms were observed and the enclosed red curve represents the dust area identified from remote sensing.

some of the recent achievements by Chinese scientists in the field of wind erosion research.

The achievements are significant, as reflected in the following areas:

- through detailed analysis of observed meteorological data, the spatial and temporal variations of wind erosion in northwest China are reasonably well understood;
- the climatic and land-surface conditions responsible for wind erosion have been analyzed and are understood in principle;
- advanced technologies, such as remote sensing using meteorological satellites, numerical prediction models and GIS, are being implemented for monitoring and assessment of dust storms; and
- a significant amount of data has been collected for the quantification of wind erosion.

While the achievements are significant, much more work is still in progress. The general trend of wind erosion research in China can be summarized as follows:

- In recent years, there has been substantial increase in support for wind erosion research. In recognizing that wind erosion is a complex problem,

Table 5. Technical parameters for the AVHRR-3 of NOAA Satellite

Channels	Spectral range (μm)	Resolution (km)	Purposes
1	0.58-0.68 (VL)	1.1	Daytime clouds, vegetation, ice-snow cover and aerosol
2	0.725-1.1 (VL)	1.1	Daytime clouds, vegetation, land-ocean boundaries and aerosol
3	3.5-4.3 (NIR)	1.1	SST, high-temperature sources and forest fire
4	10.3-11.3 (IR)	1.1	Clouds, SST, TBB and water vapour correction
5	11.5-12.5 (IR)	1.1	Clouds, SST, TBB and water vapour correction
6	1.58-1.64 (VL)	1.1	Daytime clouds, cloud-snow separation, cloud separation and drought monitoring

which involves many disciplines, comprehensive research projects at national scale are being established, which involve scientists with various backgrounds.

- Integrated wind erosion modeling systems are being developed, which combine the strengths of computational modeling, remote sensing and geographic information database. It is expected that the first generation of integrated wind erosion models will be implemented for routine wind erosion assessment and prediction in the next couple of years.

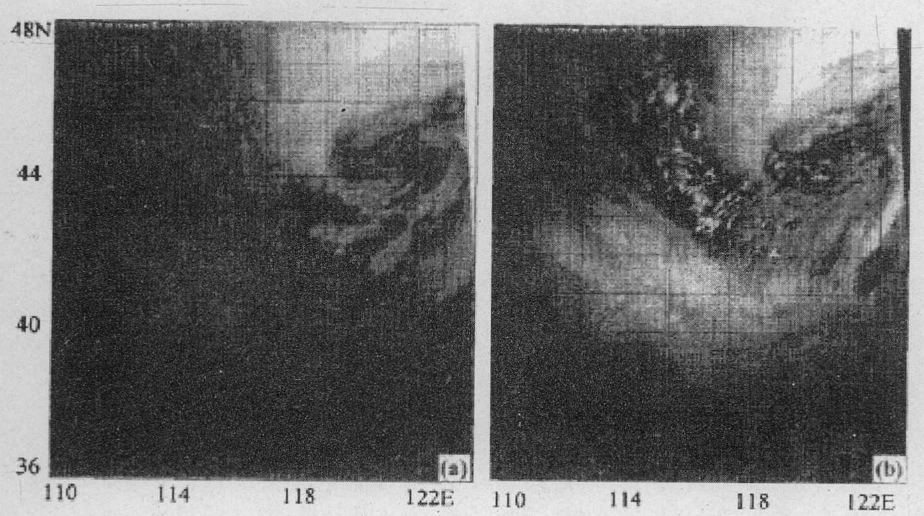


Fig. 15. Comparison of two NOAA AVHRR satellite images: (a) the ch4 image, and (b) the brightness temperature difference between ch3 and ch4 (Fang et al., 2001).

- Significant progress is being made in developing remote sensing techniques for monitoring wind erosion and for the quantification of dust concentration.
- Experimental studies on wind erosion mechanism using wind tunnels are being planned and will be carried out in the next couple of years. It is expected that these studies will lead to improved understanding of wind erosion in northwest China in particular.
- Chinese scientists are increasingly involved in international projects, such as the ACE-Asian program. The participation of Chinese scientists in such projects will benefit the international community and stimulate wind erosion research within China.

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