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Analysis of dust storms observed in Mongolia during 1937–1999

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Abstract

Climatology of dust storms in Mongolia is compiled based on observational data of 49 meteorological stations from 1960 to 1999 and compared them with data between 1937 and 1989. Three different maps of the distribution of dust storms, drifting dust and the number of dusty days are presented. The results of the analysis show that the number of days with dust storms is <5 days over the Altai, the Khangai and the Khentei mountainous regions and more than 20–37 days in the Gobi Desert and semi-desert area. The greatest occurrence of drifting dust arises around the Mongol Els area of west Mongolia.

The number of dusty days, which is derived from the sum of the number of days with dust storms and drifting dust, is <10 days in the mountainous area and 61–127 days in the Gobi Desert and the Great Lakes hollow of west Mongolia.

It is found that 61% of dust storms occur in the spring in Mongolia and a dust storm lasts on average from 3.1 to 6.0 h. About 65.5–91.0% of dust storms occur in daytime and 9.0–34.5% at night. Dust storms occur more frequently in the city region and are accompanied by surface wind speeds usually from 6 to 20 ms^{-1}. Dust storms usually occur when soil and air are dry, and 70% of dust storms occur in dry soil conditions. When dust storms occur, relative humidity averages 20–40% in Mongolia.

An important outcome of this study is the trend of dusty days between 1960 and 1999. It shows that the number of dusty days has tripled from the 1960s to 1990s and has decreased since 1990.

Keywords: Dusty days in Mongolia; Dust storm climatology; Reddish brown sand; Sand storms; Source information of dust storms

1. Introduction

Dust storms frequently occur in association with strong winds and exposed soil conditions of Mongolia, albeit little published material is available in the literature. When the phenomenon of dust and sand storms continues over several days in the Gobi Desert, Mongolian nomadic herders refer to it as the "Ugalz". Dust and sand storms disrupt human life and economic activities and result in soil erosion. One study showed that more than 70% of the pastureland area of Mongolia is under desertification, 22.1% is strongly overgrazed, and sand movement covers 7.9 million-hectares of pasturelands (Jigjidsuren and Oyuntsetseg, 1998).

According to the joint expedition by scientists of Mongolia and Russia, sand dunes with heights of 8–10 m move 15 m per year near the Ulaan-nuur Lake area, and sandy hills with heights of 5–6 m move 20 m per year near the Tavan Els area (Babaev et al., 1990). A Russian investigator (Nalivkin, 1963) showed that dust storms influence the formation of landscape and its variety and mentioned some study results of other scientists. A dust storm, which covered an area of

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470,000 ha, was observed from 9 to 12 March 1901. At that time, it was discovered that 1.8 million tons of dust deposited.

Dust storms have some negative consequences including delays and reductions in pasture for livestock, roads closure, and settlements and villages can become enshroud with sand. Furthermore, the air turbidity increases with dust storm occurrence and hence affects the radiation budget. It is important to assess dust storm impacts on climate changes in Asia as well as the World.

Some recent assessments suggest that the incoming radiation scatters back to space due to dust particles. This generates cooling rates comparable to heating by greenhouse gases (First LAS/WMO ISSDS-I, 1998; Li et al., 1996; Nickovic and Dobricic, 1996). Aerosols affect climate in several ways, they can directly and indirectly influence radiation budget of the atmosphere. Their direct effect is due to scattering, absorption and emission properties of the aerosol particles. This process results in redistribution in the atmospheric energy from solar and terrestrial radiation and causes either atmospheric heating or cooling depending on the type and spatial distribution of aerosols (First LAS/WMO ISSDS-I, 1998; Wahab, 1998). The role of the dust aerosols over the Arabian Sea is to warm the dust layer and to cool the layer below by 0.3°C. This cooling occurred as a result of the solar reduction at the low level below the dust aerosols. The effect of the dust heating over the northwest Arabian Sea takes place at the 600 and 700 mb layer (First LAS/WMO ISSDS-I, 1998; Mohalfi, 1998).

Several significant meteorological phenomena occur in association with dust storms. One of them is called the "Voikov phenomenon", which causes an increase in air temperature. Bugaev (Seredkina, 1960) concluded that dust and sand particles can be lifted from heated soil, and can be heated again in the atmosphere, and heated rays from them could be transmitted to the surrounding air. Therefore, it becomes warm during dust and sand storms.

Blaketein (Nalivkin, 1963) observed that when dust and sand storms occur, the electric field tension in the air increases. They called it "electrically charged dust". During the period of dust and sand storms, iron materials and particulates become electrically charged in the Gobi Desert of Mongolia.

Dust storms in Mongolia have been studied for some time. A Mongolian scientist, Tuvdendorj studied climatology of dust storms and synoptic situations for the formation of dust storms using 10 years of data from 24 meteorological stations obtained between 1956 and 1965. It was the first published study of dust storms in Mongolia (Tuvdendorj, 1973, 1974).

Researchers at the Institute of Geography and Permafrost in the Scientific Academy of Mongolia performed experiments on sand movement measurement near Zamiin-Uud city between 1982 and 1985, and the results are of special interest (Lomborenchin, 1983). Luvsandendev and Jamiyanaa (1991) calculated dust and sand movements in Mongolia, using a turbulent diffusion equation. They compared their calculated value of transported dust and sand with a measured value. In their study, the calculated value was 1990.7 tons and the experimental measured value was 1443.9 tons over a 0.5 km^2 of land field near Zamiin-Uud city.

The purpose of the present study is to investigate in detail the frequency and distribution of dust storms over the territory of Mongolia. Using many years of data, we have developed a dust storm prediction method that is being used for daily weather forecasting practice (Jugder and Natsagdorj, 1992; Natsagdorj and Jugder, 1993). This paper will describe specific source information on dust storms and frequencies.

2. Data used

Wind speed is measured by wind-vanes at most meteorological stations in Mongolia (more than 100 stations), and at remote sites, 12–13 stations a recording anemometer has been used since 1985. However, dust storm occurrence is related to soil conditions, vegetation cover, and wind speed. Dust storm observations are made meteorological observers in Mongolia. This is a subject in process and depends on observational practice, established guidance, regulations, and observer's skill. Various analyses of dusty days have been reported in Mongolia (Tuvdendorj, 1973, 1974; Natsagdorj, 1982; Natsagdorj and Jugder, 1992; Jugder, 1999). For example, observers recorded numerous dust storms, and relatively few drifting dust at the Zamiin-Uud station between 1956 and 1966. However, since 1967, both dust storms and drifting dust at this station have been routinely reported. In this same manner, dust storms were recorded at the Matad and the Bayandelger stations between 1940 and 1958. The average number of days with dust storms was 18.9 and 27.1 at the Bayandelger and the Matad stations, respectively, between 1940 and 1959 and 5.3, and 6.8 at those stations between 1960 and 1989, respectively. Therefore, the average number of days with dust storms has decreased in last 30 years and the average number of days with drifting dust has increased at those stations during that period of 1960–1989.

In order to determine climatology of dust storms in this study, we have used daily observational data of dust storms from the 49 meteorological stations in Mongolia recorded between 1960 and 1989, and used additional dust storm data between 1937 and 1989, and between 1975 and 1999. We have more detailed study on dust storms and this represents the most comprehensive study of dust storms in Mongolia.

3. Study results

We analyzed all of the dust storm data since 1937, and we obtained the average number of dusty days with dust storms in two different periods; between 1937 and 1989, and between 1960 and 1999 and compared together at every station. We found that the difference between the average numbers of days with dust storms in the different periods was not significant. Hence, we present here only the last 30-year's average frequency of dust storms. The locations of stations used in this study are presented in Fig. 1.

3.1. Number of days with dust storms

The distribution of the number of days with dust storms is shown in Fig. 2. The number of days with dust storms is <5 days over the Khangai, Khuvusgul and Khentei mountainous areas of Mongolia, 10–17 days over the area of Great Lakes hollow, and 20–37 days over the desert and the steppe-desert area in Mongolia.

The highest frequency of dust storms is over the three areas in the Gobi Desert in Mongolia, such as the south side of the Altai Mountains and around Ulaan-nuur Lake and Zamiin-Uud. It should be noted that the distribution of dust storms coincides well with the distribution of strong wind (Natsagdorj, 1982; Jugder, 1999) and soil conditions. For instance, dust storms commonly occur at places where the soil is loose and sandy, and that experience a high frequency of strong winds. Dust storms occur less frequently in the mountainous areas because of thick vegetation, snow patches, and light wind on the lee slope. In the steppe, winds are relatively strong, dust storms occurrence is low with thick grass and snowfall. Dust storms occur more frequently around some cities, in fact because of man-made soil erosion and urbanization. The frequencies of dust storms around cities are drawn as small circles on the map (Fig. 2). Such cities are Muren,

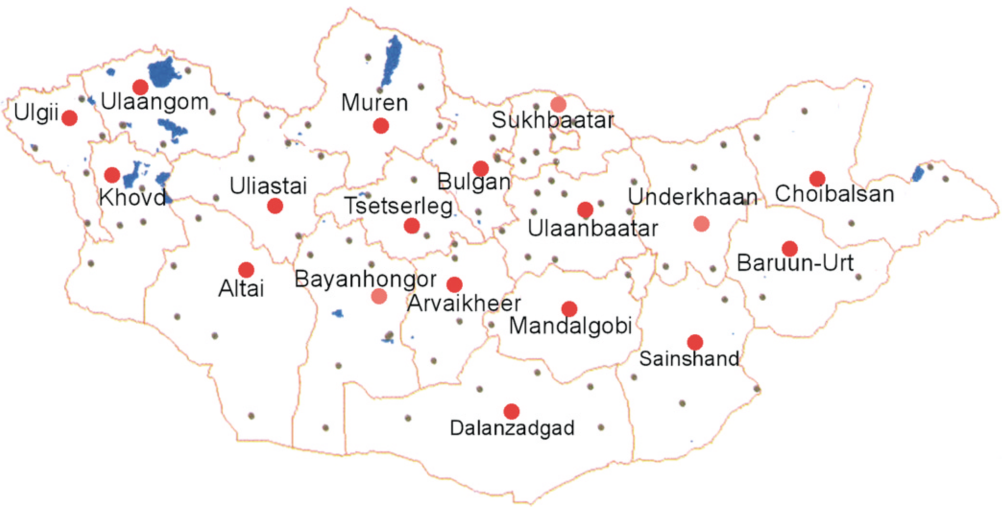

Fig. 1. A map of Mongolia.

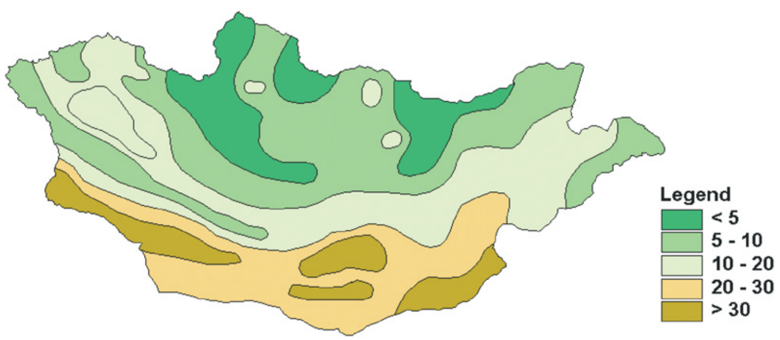

Fig. 2. Number of days with dust storms observed in Mongolia.

Bulgan, Kharaa, Ulaanbaatar and Binder in the north of Mongolia.

3.2. Number of days with drifting dust

The distribution of drifting dust is shown in Fig. 3. It is seen that the number of days with drifting dust is more than the number of days with dust storms. The maximum number of days with drifting dust is 110 days over the Mongol Els area (the Durvuljin station's data), 60–70 days over the south side of the Altai Mountains and the Arts Bogd Mountain area.

The number of days with drifting dust is also large around the cities. For example, it totals 16.3 days at the Ulaanbaatar station, which is located in the city, and 4.2 days at the Buyant-Ukhaa station, which is located outside the city.

3.3. Number of dusty days

The distribution of dusty days is shown in Fig. 4. The number of dusty days is <10 over the Khangai, the Khentei and the Khuvusgul mountainous areas, and 61 to 127 over the Great Lakes hollow and the Gobi Desert area. The number of dusty days ranges from 91 to 120 over the Gobi on the south side of the Altai Mountains, and about 80 for areas surrounding the Arts Bogd Mountain in the Gobi Desert. The highest occurrence of dusty days is around the Mongol Els area.

3.4. Annual and daily variations of dust storms

There is a clear annual variation in dust storm occurrences in Mongolia. In association with the movement of the middle-latitudinal cold frontal belt, the highest frequency (61%) of dust storms occurs in spring and a second maximum frequency (22%) occurs in autumn (October and November) in Mongolia. The annual minimum frequency (7%) occurs in summer, a period when low-pressure fields with a weak pressure gradient predominates, and (10%) in winter, in which cyclonic activity is weak and the air is most stable. Annual variations in dust storm occurrences in the Gobi (station Dalanzadgad), steppe (station Baruun-Urt), and mountainous regions (station Muren) are shown in Fig. 5.

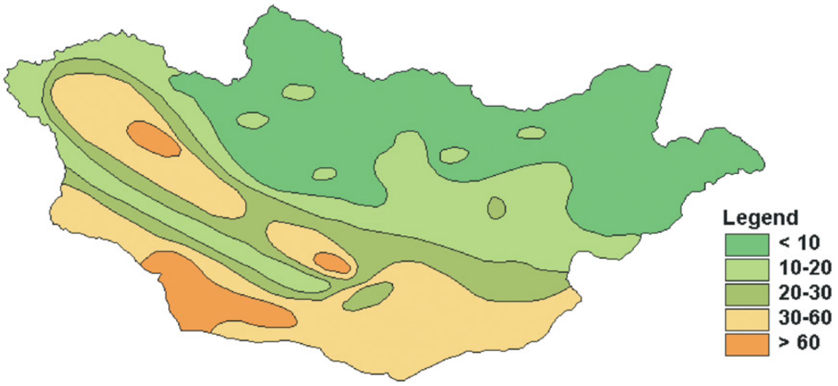

Fig. 3. Number of days with drifting dust observed in Mongolia.

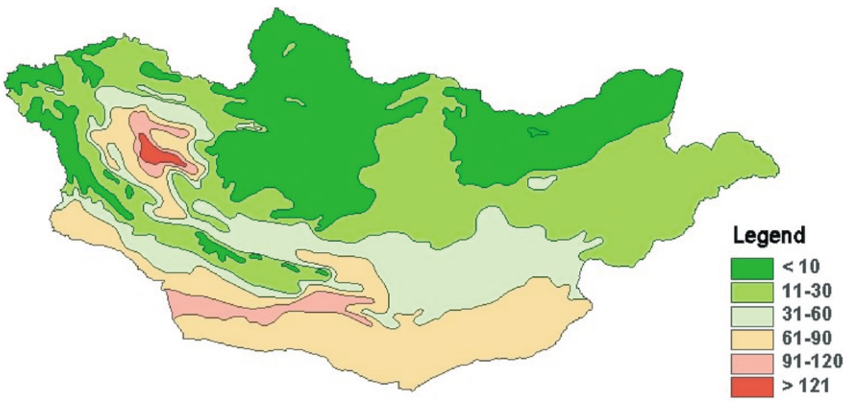

Fig. 4. Number of dusty days observed in Mongolia.

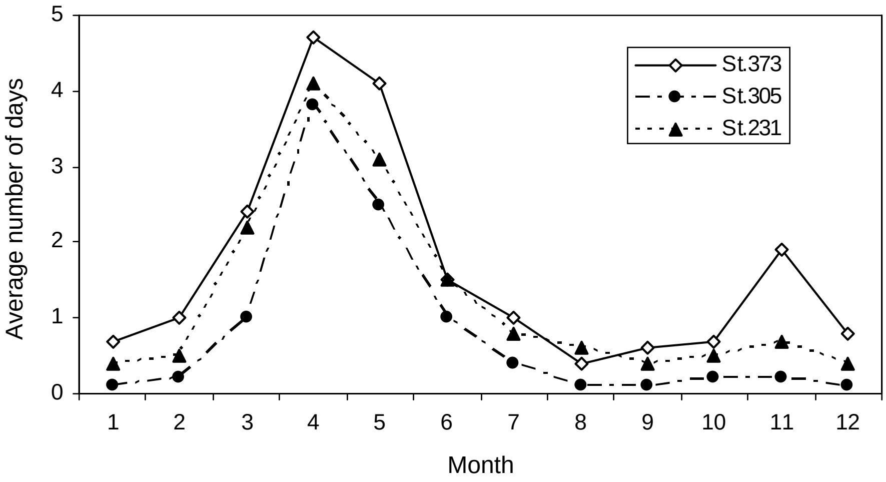

Fig. 5. Average number of days with dust storms between 1960 and 1989. From the top, St.373-Dalanzadgad station; St.305-Baruun-Urt station; St.231-Muren station.

Table 1
Daily variation of dust storms (frequency %)

Type	Area	Season	Time interval (h)								Night time	Day time
			21–24	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–9	9–21
Dust storm	Gobi	Winter	8.4	8.6	9.2	7.0	13.0	19.8	20.3	13.7	33.2	66.8
		Spring	7.7	5.2	5.0	6.5	12.9	20.3	23.8	18.6	24.4	75.6
		Autumn	7.1	6.4	6.0	7.7	13.9	21.9	24.3	12.7	27.2	72.8
	Steppe	Winter	3.0	4.0	2.0	4.9	25.7	32.7	20.8	6.9	13.9	86.1
		Spring	4.7	3.0	2.7	7.4	16.7	25.1	25.4	15.0	17.8	82.2
		Autumn	4.0	2.6	2.0	5.1	22.2	28.3	24.3	11.5	13.7	86.3
Drifting dust												
	Gobi	Winter	7.1	8.9	8.6	9.9	16.2	21.5	18.5	9.3	34.5	65.5
		Spring	5.3	5.6	5.5	6.4	16.3	23.4	22.7	14.8	22.8	77.2
		Autumn	6.5	6.5	6.9	7.7	15.9	22.9	22.9	10.7	27.6	72.4
	Steppe	Winter	2.0	2.0	1.0	4.0	25.0	36.0	23.0	7.0	9.0	91.0
		Spring	2.3	1.7	1.7	7.7	19.7	29.8	25.7	11.4	13.4	86.6
		Autumn	2.0	1.0	2.0	6.0	24.0	34.0	25.0	6.0	11.0	89.0

The annual distribution of dust storms is significantly variable at the different stations. For example, with respect to geographical condition, dust storm occurrences in winter do not appear in the Uvs Lake hollow, but its frequency is 29.6% at the Bulgan Soum (the Saikhan station) of Umnigobi Aimag (Jugder and Natsagdorj, 1992).

Dust storms have a clear daily variation in the Gobi and the steppe area in Mongolia. The daily variation increases in daytime and decreases in nighttime. In daytime, the heating of the ground surface produces wind and unstable conditions of the air and in nighttime, the opposite occurs.

In order to clarify daily variation of dust storms, we obtained their frequency at every 3 h in spring, autumn and winter in the Gobi and steppe regions (Table 1). The daily variation of dust storms for spring in the Gobi is shown in Fig. 6. The highest frequency (65.5–91.0%) occurs in daytime and the lowest (9.0–34.5%) at night in the Gobi and steppe areas of each season.

3.5. Duration of dust storms

For a study of the duration of dust storms, we used the beginning and ending times of dust storms obtained from 1975 to 1999. Monthly mean and annual mean durations of dust storms and drifting dust in the Gobi and the steppe area in Mongolia correlate well with the frequencies of dust storm occurrence. Where frequency is high there is a longer period of dust storms. The annual mean number of hours of dust storms is >100 h over the Gobi on the south of the Altai Mountains and

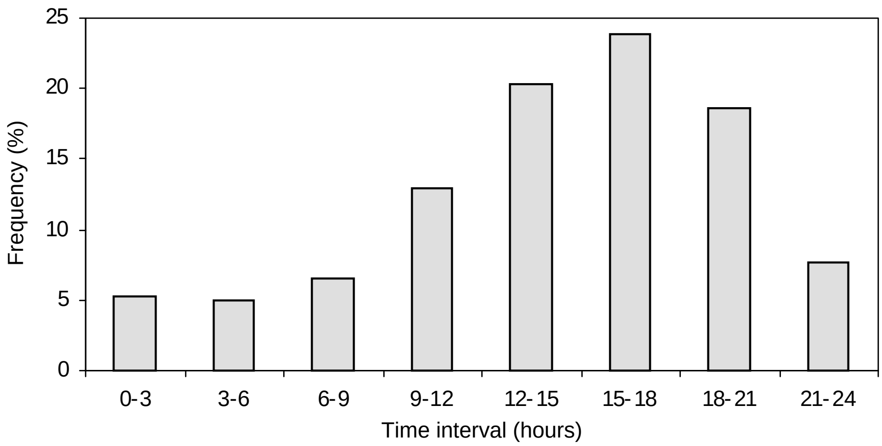

Fig. 6. The daily variation of dust storms for spring in the Gobi.

the territory of Umnigobi Aimag. The number of hours of dust storms is about 364 h at the Saikhan station in this Aimag. The maximum length of drifting dust is about 485 h around the Mongol Els area.

The duration of the combinations of dust storms and drifting dust is longer than 200 h per year over the Gobi on the south of the Altai Mountains, Umnigobi Aimag and around the Mongol Els area. For example, it is about 493 h at the Tooroi station in the south of the Altai Mountains, about 614 h at the Saikhan station of Umnigobi Aimag, and about 508 h at the Durvuljin station in the Mongol Els area.

We also calculated the average duration of a dust storm occurrence. This was done by first determining the duration of dust storm occurrences over 15 years (10458 h in the Zamiin-Uud). After that, the figure was divided by the total number of dust storm occurrence over the 15 years (233 cases over 15 years in Zamiin-Uud). In this way, we obtained the average duration of dust storm occurrence at other stations in the Gobi (Table 2).

Fig. 7 shows the average duration of a dust storm. A dust storm (also a drifting dust) lasts on average from 1.6 to 6.0 h, sometimes more than 12 h in the Gobi and <3 h (60–80%) in the mountainous area. There is also a relationship between frequency and duration. If the average duration of a dust storm (also a drifting dust) occurrence is more than 6 h then its frequency decreases. This is shown for the Gobi in Fig. 7, and for the mountainous areas in Fig. 8. The duration of a dust storm occurrence is longer in spring and shorter in summer.

Table 2
Average duration in a dust storm (a drifting dust) occurrence (h)

Station	DS	DD
Baitag	3.5	3.4
Tooroi	4.0	3.1
Ekhiin gol	7.1	5.4
Tonkhil	4.6	4.8
Altai	3.3	3.3
Gurvantes	6.2	4.8
Saikhan	8.5	4.6
Tsogt-Ovoo	5.4	3.0
Dalanzadgad	4.6	3.2
Khanbogd	4.1	3.0
Bogd	2.9	3.6
Saikhan–Ovoo	2.8	2.4
Mandalgobi	3.9	2.4
Choir	5.3	4.6
Sainshand	3.3	2.1
Zamiin-Uud	4.7	4.3

DS—dust storm; DD—drifting dust

4. Meteorological conditions during dust storms

Surface wind: In general, southwesterly, westerly and northwesterly winds predominate during dust storms. Surface wind speeds are usually from 11 to 20 ms^{-1} during dust storms, and 6 to 15 ms^{-1} during drifting dusts. If the surface wind speed is $<5\,ms^{-1}$, a dust storm does not form. The frequency of surface wind speed during dust storms is shown in Table 3 and Fig. 9.

Visibility: Visibility is 1 km or less in 30% of all dust storm occurrences, and it is usually from 10 to 20 km during dust storms.

Relative humidity: Relative humidity is low during dust storms because they usually occur at daytime. The frequency of relative humidity during dust storms and drifting dust is shown in Table 4. In addition, variations of relative humidity associated with dust storms are shown in Fig. 10. Many dust storms occur with relative humidity between 21% and 40% in the source areas.

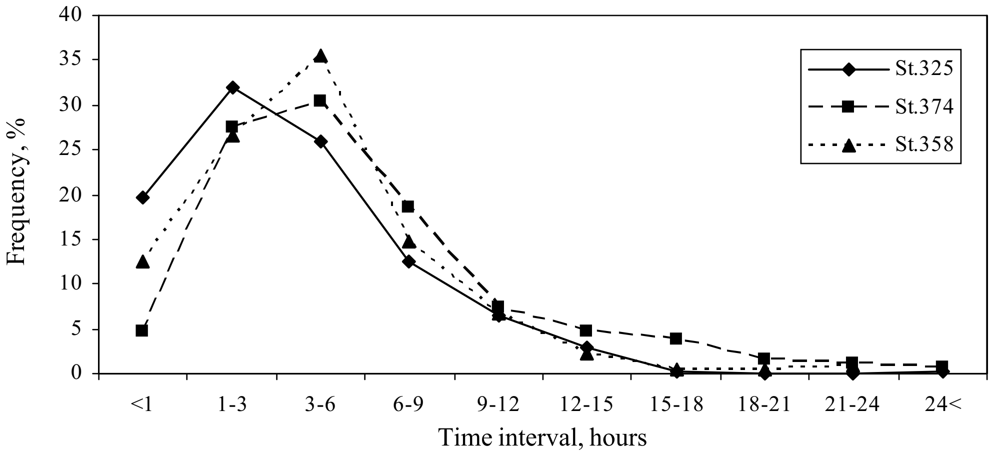

Fig. 7. Average duration of a dust storm (time interval) in the Gobi. From the top, St.325-Tooroi station; St.374-Gurvantes station; St.358-Zamiin-Uud station.

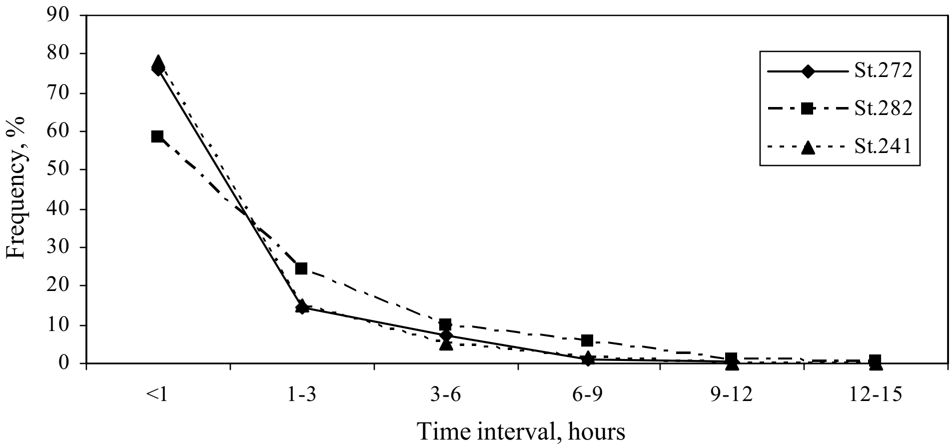

Fig. 8. Average duration of a dust storm occurrence in the mountainous area. From the top, St.272-Uliastai station; St.282-Tsetserleg station; St.241-Baruunharaa station.

Table 3
Frequency (%) of surface wind speed with dust storms and drifting dust

Type	Area	Surface wind speed (ms^{-1})					
		$\leqslant 5$	6–10	11–15	16–20	21–25	$26\leqslant$
Dust storm	Gobi	—	11.5	46.5	38.4	2.3	1.3
	Steppe	—	16.0	38.0	41.0	3.0	2.0
Drifting dust	Gobi	0.1	27.2	62.1	10.6	—	—
	Steppe	2.0	52.0	33.0	13.0	—	—

4.1. Transportation of dust and sand particles

The land area covered by sand and the movement of sand due to man's destruction of trees, shrubs and brush in the Gobi are increasing in Mongolia. Such areas are seen in the south and the east sides of the Mongol Els area, the salt reserve land area in the Gurvantes Soum of Umnigobi Aimag, the environments of Zamiin-Uud, Zuunbayan, Orog Lake, Khongoriin Els, and the Ulaan-nuur Lake. Soil erosion takes place due to strong dust storms; one example shows that from 27 to 30 November 1991 a severe dust storm with maximum wind speeds of from 34 to 40 ms^{-1} occurred covering almost the entire territory of Mongolia (12 Aimags). According to our calculations, 662.5 million tons of soil moved from one place to other place in this Aimag. (Assuming a top soil with a 0.5 cm depth blowing away from half the territory in the Umnigobi Aimag and the density of sand equal to 2.65 $g\,cm^{-3}$).

In relation with the dust storm, much dust and sand particles lifted to the atmosphere by strong wind in the Gobi and city areas and migrated faraway toward southeast. Long-range transport of dust from a source

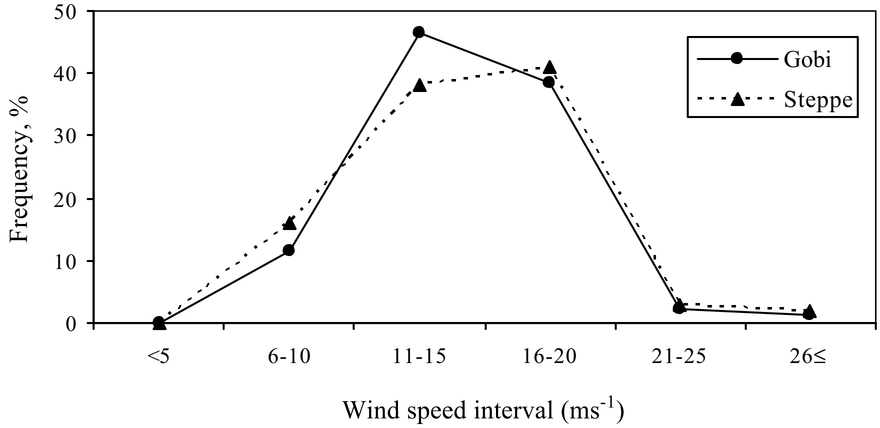

Fig. 9. Frequency (%) of surface wind speed.

Table 4
Frequency (%) of relative humidity (%) during dust storms and drifting dust

Type	Area	Relative humidity (%)							
		⩽10	11–20	21–30	31–40	41–50	51–60	61–70	71⩽
Dust storm	Gobi	0.2	15.9	24.7	22.5	16.4	9.5	5.1	5.7
	Steppe	0.9	10.3	22.7	22.6	19.3	11.4	6.3	6.5
Drifting dust	Gobi	0.3	12.4	23.1	21.5	18.0	12.0	6.5	6.2
	Steppe	1.0	12.0	23.0	26.0	20.0	9.0	5.0	4.0

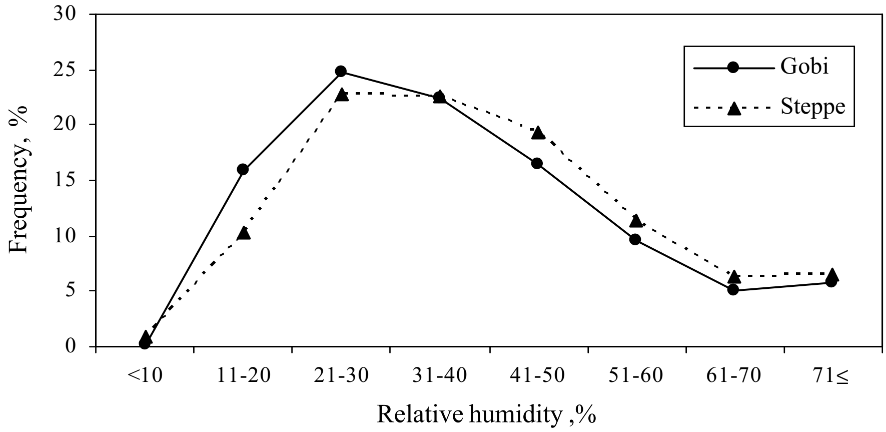

Fig. 10. Frequency (%) of relative humidity (%) during dust storms.

area can be increased air turbidity and decreased air visibility. It is called a "dust haze". Chung et al. (2001) refers this stage as "significant dust fall".

5. Number of dusty days and trend

It is clear that dust storms occur at places with less vegetation cover, dry and loose sandy (dusty) soil, when wind speed reaches a certain value; 8 ms^{-1}. Both dust storms and drifting dust have an important effect on soil erosion. Therefore, we are able to estimate, where desertification process takes place, by using the number of dusty days recorded over many years.

We have derived the number of dusty days per year from sum of the number of days with dust storms and drifting dust obtained from 34 meteorological stations in Mongolia from 1960 to 1999 (Fig. 11).

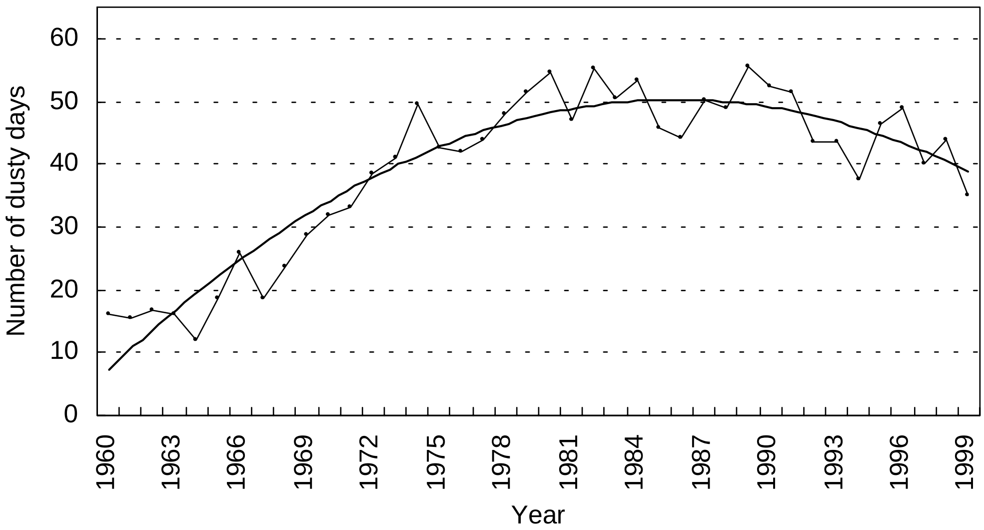

Fig. 11. Number of dusty days in Mongolia and its trend.

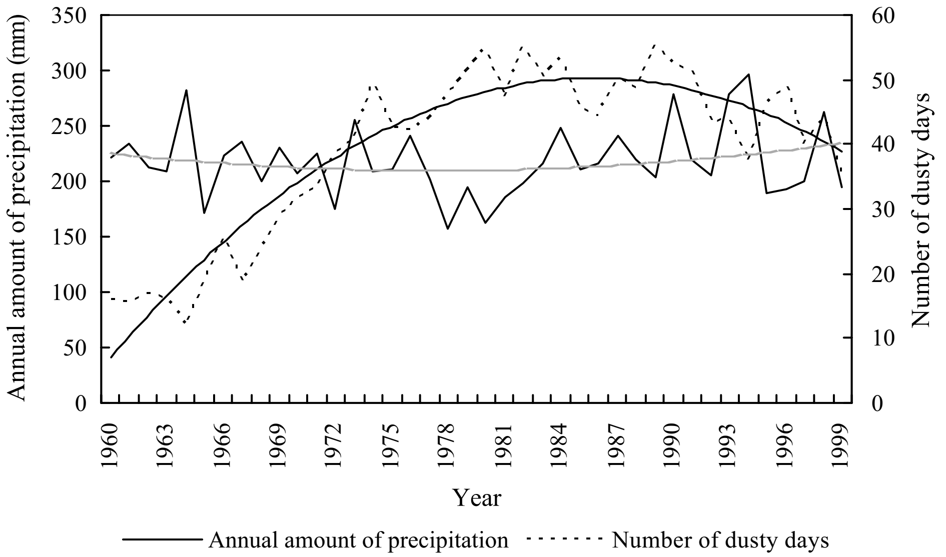

Fig. 12. Annual amount of precipitation and dusty days in Mongolia.

It can be seen in Fig. 11 that the number of dusty days was about 15 days in the 1960s and about 50 days in the 1980s, an increase of more than 3 times. Nevertheless, the number of dusty days has been decreasing since 1990. These variations in the number of dusty days may be linked to human activity and the amount of annual precipitation. Since 1960, populated areas increased, the number of transport means such as lorry, truck, tractor increased. The natural pasturelands overgrazed, and soil erosion considerably took place due to increasing of cultivated land area near settlements. Moreover, the amount of annual precipitation has "decreased" since the mid 1960s until 1980s when compared to the end of 1950s. In addition, the driest period was in the 1980s (Natsagdorj et al., 1999).

According to Fig. 12, annual amount of precipitation and dusty days have a reverse correlation and they coincided well negatively. In the last 10 years, particularly since 1990–1994, annual precipitation has increased and its trend has a slight increase while dusty days has dropped down with a decreasing trend in Mongolia. This may be the cause of dusty days decreasing in the last 10 years. Other explanations must be sought to clear up uncertainty by a further study.

6. Conclusions

In this study, we have used data of 1937–1999 for the comparison with previous dust storm studies, and we have carried out a detailed analysis on the climatology of dust storms in Mongolia. The study results are as follows:

(1) We have shown the distribution of number of days with dust storms in Mongolia, using data obtained between 1960 and 1989 from 49 meteorological stations.
(2) The number of days with dust storms is <5 days over the Altai, the Khangai and the Khentei mountainous regions, is more than 20 days in the Gobi Desert and steppe-desert area, and 30–37 days over the south side of the Altai Mountains, the Bulgan Soum of Umnigobi Aimag and the Zamiin-Uud city of Dornogobi Aimag.
(3) The number of days with drifting dust is <10 days over the Altai, the Khangai, the Khuvusgul and the Khentei mountainous regions, and more than 20 days in the Gobi Desert, semi-desert area and the Great Lakes hollow, and 61–110 days over the Mongol Els area and the south side of the Altai Mountains. The most occurrence of drifting dust is around the Mongol Els area.
(4) The number of dusty days, which is derived from sum of the number of days with dust storms and drifting dust, is 61–127 days in the Gobi Desert and the Great Lakes hollow.
(5) Dust storms are occurring more frequently in the city region. For example, the number of days with drifting dust is about 16 days in Ulaanbaatar city and about 4 days at Buyant-Uhaa in the outskirts.
(6) However, frequency of dust storms depends on the period examined. The average day with dust storms between 1960 and 1999 can be used as a frequency standard. It is similar to an average day with dust storms between 1937 and 1989.
(7) 61% of dust storms occur in the spring in Mongolia.
(8) About 65.5–91.0% of dust storms occur between 0900 LST and 2100 LST in day and 9.0–34.5% at night.
(9) The duration of dust storms is longer than 100 h in the Gobi Desert per year.
(10) Average durations of a dust storm and a drifting dust occurrence are about 4.6 and 3.6 h, respectively. A dust storm lasts in average from 3.1 to 6.0 h.
(11) Wind speed is usually from 11 to 20 ms^{-1} during dust storms, and from 6 to 15 ms^{-1} during drifting dusts. Westerly and northwesterly winds predominate during dust storms.
(12) Dust storms usually occur when soil and air are dry. Seventy percent of dust storms occurred in dry soil conditions. When dust storms occur, relative humidity averages 20–40% in Mongolia.
(13) An important outcome of our study is the trend of dusty days between 1960 and 1999. The trend shows that the number of dusty days has increased tripled from the 1960s to 1990s and then began decreasing in the recent decade from 1990.
(14) The Mongolian Gobi is a source area for the formation of dust storm in East Asia.

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