Characteristics of Dust Emission in the Mongolian Steppe during the 2008 DUVEX Intensive Observational Period

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Abstract

The joint Japan-Mongolia-USA project DUVEX (Dust-Vegetation Interaction Experiment) was designed to develop a biogeophysical model which can simulate dust emission and ecosystem processes over the vegetated land surface. Dust emission processes have been investigated mostly on bare land, and there is very little information about vegetated land. Thus, intensive observations were conducted of a dust event that occurred on the Mongolian steppe on 24 April 2008.

Meteorological and dust elements (e.g., saltation flux, visibility, dust concentration) and land-surface parameters (e.g., roughness length, vegetation cover, and the ground-based normalized difference vegetation index) were measured. During the event (from 13:00 to 18:00 LST on 24 April), the threshold wind speed at 1.54 m height, which is the minimum wind speed inducing saltation of particles ranging from 30 to 667 μm in diameter, was 8.9 m s^{-1} on a land surface with 7.2% vegetation cover with dead brown leaves, a small roughness length (0.0058 m), and a very dry sandy soil at 0−5 mm depth (water content, 0.002 g g^{-1}). For comparison with previous studies, the threshold wind speed value was converted to the values at the heights in each study by using the logarithmic law of wind profile. Our value is close to the SYNOP-derived values for the same area, but larger than ground-observed and SYNOP-derived values for East Asian deserts.

1. Introduction

Severe dust events occur frequently in the arid regions of East Asia, particularly in the Taklimakan and Gobi deserts and on the Loess Plateau (e.g., Kurosaki and Mikami 2005; Shao and Dong 2006; Zhang et al. 2008). Aeolian dust produced in these arid regions increasingly affects human health and local ecosystems in East Asia, not only in the source regions but also in downwind regions.

Efforts have been made to develop integrated dust-modeling systems that couple models of atmospheric, land-surface, and aeolian processes with real-time dust observations and databases of land-surface parameters in order to adequately represent dust storm dynamics and the controlling environmental factors (Shao and Dong 2006). In most dust models, land-surface conditions such as soil particle size distribution, soil surface characteristics, vegetation coverage, and the roughness frontal area index are expressed in an emission scheme. However, to date, ground-truth data to validate the representation of the scheme are lacking owing to the difficulty of making the necessary observations. Recently, new instruments for measuring dust emissions have been developed, and the physics of dust emissions have been gradually clarified (Mikami et al. 2005; Etyemezian et al. 2007). However, most results have been obtained for bare land, and little is known about dust emissions from vegetated land. The threshold wind speed (hereafter, threshold speed) and the friction velocity for dust emission likely change depending on vegetation cover (Kimura et al. 2009), surface soil water content (Ishizuka et al. 2005; Kimura et al. 2009), and snow cover (Kurosaki and Mikami 2004). Detailed relationships among dust emissions and these variables are not well known for vegetated land in East Asian dust outbreak areas.

We investigated the relationship between threshold speed and vegetation conditions determined by ground and satellite observations during the intensive observational period (IOP) of 24−27 April 2008. This study was carried out by the Global Center of Excellence for Dryland Science program of Tottori University.

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2. Method

2.1 Site description

The dust observing site (DOS) is located at Bayan Unjuul, Mongolia (47°02′38.5″N, 105°56′55″E), which is characterized by a semi-arid climate, defined by an aridity index (UNEP 1997) between 0.20 and 0.50, and its steppe vegetation (see Fig. S1 in Supplement 1). Long-term meteorological observations have been made at a site approximately 600 m southeast of the DOS at an Institute of Meteorology and Hydrology of Mongolia (IMH) monitoring station, and a 300 m × 300 m area that has been fenced since June 2004 to prevent grazing by livestock is located just east of the DOS (Fig. 1). The DOS has an area of 50 m × 35 m and has been fenced since 24 April 2008 to keep herders and animals out of the DOS. The vegetation conditions inside the fence were maintained as almost the same as those for the outside, by introducing the grazing of livestock inside the fence regularly. The DOS is located such that it is open on the north and west directions from which strong winds blow during April, according to automatic weather station observations made in the NG area (Fig. 1).

Average annual precipitation at the IMH station from 1995 to 2005 was 163.0 mm, concentrated in summer (May−August, 124.4 mm), and the annual mean temperature was 0.1°C, with a maximum of 22.9°C in July and a minimum of −20.6°C in January. The soil is frozen during the 6-month winter (October −March) (Shinoda et al. 2010). In general, May to August is the period of plant growth in the Mongolian grasslands (Shinoda et al. 2007). This region has experienced reduced summer precipitation since the mid-1990s, with severe droughts (< 90 mm) in 2002 and 2005−2007. In central Mongolia, where the DOS is located, dust storms occur from March to May, peaking in April (Natsagdorj et al. 2003; Kurosaki and Mikami 2005). The Mongolian steppe is characterized by a distinct seasonal change in the threshold speed (which is the lowest in spring), whereas no such change is

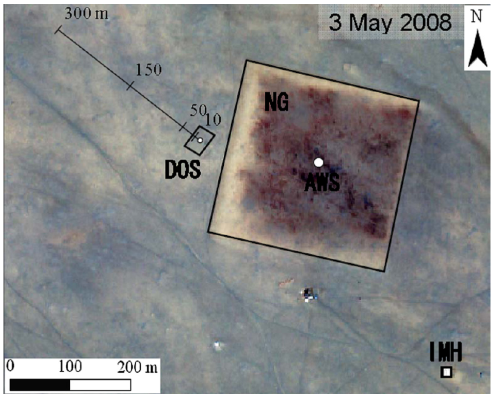

Fig. 1. Layout of the DOS illustrated on the QuickBird false color image on 3 May 2008. The locations of the DOS, the no grazing (NG) area with the automatic weather station (AWS), IMH station, and the soil and vegetation survey transect are shown. Note that sands were trapped mainly downwind of the western fence in the NG area.

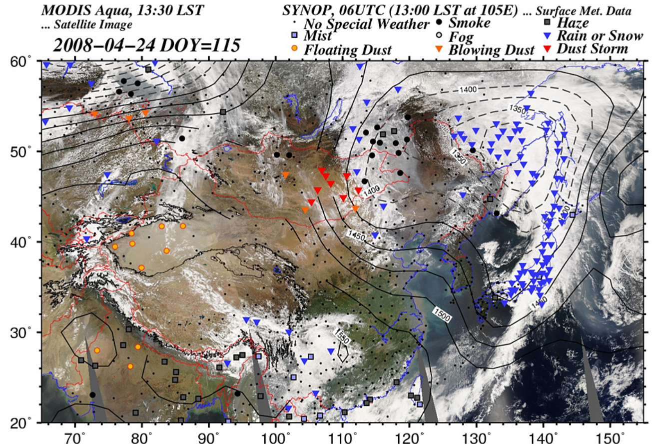

Fig. 2. Surface weathers, geopotential heights at 850 hPa at 14:00 LST (06:00 UTC), and MODIS true color image around 13:30 LST (05:30 UTC) on 24 April 2008.

observed in the neighboring Gobi Desert (Kurosaki and Mikami 2007). Note that the threshold speed is related directly to land-surface conditions.

The DOS is co-dominated by perennial grasses (*Stipa krylovii*, *Agropyron cristatum*, and *Cleistogenes squarrosa*), by forbs (*Artemisia adamsii* and *Chenopodium aristatum*), and by small shrubs (*Caragana* spp.) (Shinoda et al. 2010). Most plant roots are distributed in the top 20 cm of soil. The bulk density of the surface horizon (0−5 cm depth) is approximately 1.5 g cm^{-1} (Nakano et al. 2008).

In Mongolia, the steppe has long been used for livestock grazing, and the village to which the DOS belongs had allowed the site to be overgrazed in the preceding August (2007), exceeding twice the pasture livestock capacity, which was reduced in the severe drought conditions (IMH 2007).

2.2 Meteorological and dust observations

Meteorological observations at the DOS included air temperature, humidity, air pressure, wind speed/direction, shortwave/longwave radiation, photosynthetically active radiation, and precipitation, while soil observations included soil temperature, heat flux, and water content (see Table S1 in Supplement 2). An instrument that can measure particle sizes less than 10 µm (PM10) was used to measure the dust concentration, and visibility was also measured. A sand particle counter (SPC) was used to observe the number of saltation particles of different particle sizes (Mikami et al. 2005; Ishizuka et al. 2005). The measurable particles ranged from 30 to 667 µm in diameter are divided into 32 channels. The saltation mass flux at heights z, $q(z)$, was evaluated by integration of the saltation mass flux of saltation particles of volume-averaged diameter D_{si} in bin number i at a height z, with the following equation:

$$q(z) = \sum_{i=1}^{N_{\max}} \hat{q}(z, D_{\mathrm{si}}), \tag{1}$$

where $q(z, D_{\mathrm{si}})$ is the saltation mass flux at a diameter D_{si} and a height z, assuming spherical particles. All data were averaged on a 1-min interval for analysis. Long-term observations, following the IOP, continue at the site.

In addition to the site measurements, we performed a synoptic analysis of the SYNOP report, objective-analysis data of geopotential height at 850 hPa produced by the National Centers for Environmental Prediction (NCEP), and the MODerate resolution Imaging Spectroradiometer (MODIS) Aqua true color image for 24 April 2008, when a dust storm occurred over a wide area of the steppe.

2.3 Estimation of roughness length

We determined roughness length z_0 from observed wind speed profiles for neutral atmospheric stability conditions using a computerized graphical procedure. Under neutral conditions, the wind speed profile can be expressed as

$$u = \frac{u_*}{k} \ln \frac{z}{z_0}. \tag{2}$$

Here, u is wind speed (m s^{-1}), $u*$ is the friction velocity (m s^{-1}), k is von Karman's constant (= 0.4), z is height (m), and z_0 is the roughness length (m). In this analysis, the roughness length is taken as the value of z_0 when the maximum coefficient of determination (at least 0.999) is achieved between u and ln(z). The roughness length is then obtained from the intercept of the plotted line on the ln(z) axis. The slope of the plotted straight line is $u*/k$. The Richardson number, Ri, is used as an index to determine the stability of the air. This parameter was calculated by using the vertical gradients of potential temperature and horizontal wind speed. In the present analysis, only data for neutral conditions ($-0.05 < Ri < 0.05$) was considered.

2.4 Land-surface observations

During the IOP, vegetation cover was measured in the northwestern part of the DOS by distinguishing the vegetation leaf and stem from soil using a digital image of a 1 m × 1 m quadrate, which is approximately the view range of the spectral irradiance instrument. At the same location, spectral irradiance (W m^{-2} µm^{-1}) > 3 nm was observed with the spectral irradiance instrument (EKO Inc., MS-720) for estimation of the ground-based normalized differential vegetation index (NDVI). Also, the width of the remnant plant stand left after grazing was determined, and the top 10-cm soil layer was sampled and its texture and chemical properties were analyzed (Table 1).

MODIS NDVI data (16-Day L3 Global 250 m, 14−29 April 2008) was used for the broad area which is most likely to affect dust emission. The fetch was assumed to be 300 times the wind speed measurement height (top height, 3.1 m), that is, about 1 km (Oke 1978). Because the prevailing wind is northwesterly, the average of 16 NDVI values detected within one square kilometer northwest of the DOS was used.

3. Results and discussion

3.1 Dust event on 24 April 2008

During the IOP, a large-scale dust event occurred on 24 April

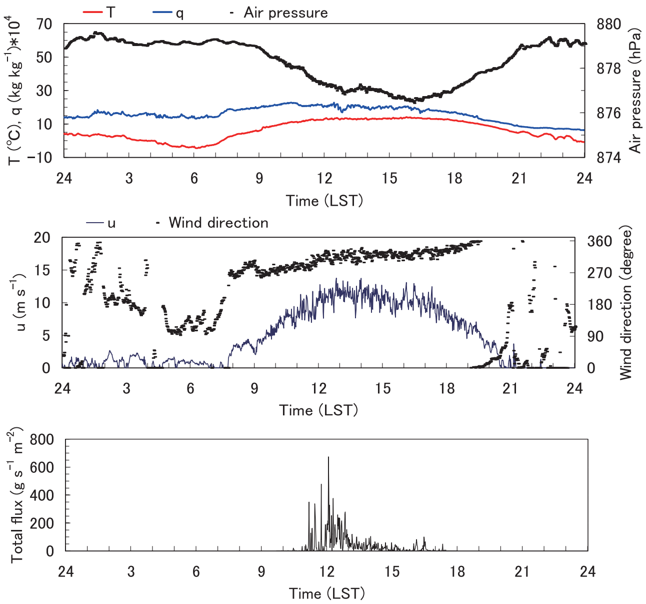

Fig. 3. Time series of temperature T (°C), specific humidity q (kg kg^{-1}), air pressure (hPa), wind speed u (m s^{-1}) at 1.54 m, wind direction (degrees), and total saltation flux (g s^{-1} m^{-3}) on 24 April 2008.

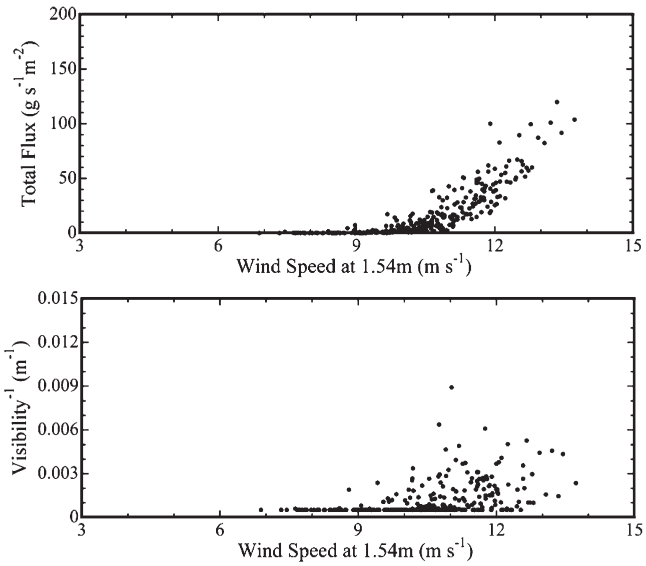

Fig. 4. Relationships of total saltation flux at the height of 0.06 m (g s^{-1} m^{-3}) (top) and the reciprocal of visibility (m^{-1}) (bottom) with wind speed at the height of 1.54 m on 24 April 2008.

in association with the southeastward-moving low pressure system whose center passed in the northeast of our site (Fig. 2). Figure 3 shows the time series of atmospheric conditions at 1.54 m and the total saltation flux. Around 09:00 LST, in conjunction with the approaching low pressure, the wind speed increased. Subsequently, the saltation flux increased with the increasing wind speed. The duration of this event was 6−7 hours, during which the wind direction was almost constant from the northwest.

Strong winds around 12:00 LST resulted in a flux larger than that produced by similarly strong winds during the following hours. This is likely because the soil dug out of the construction site of the DOS fence was blown off to the SPC at the beginning of the observations, giving a bias to the flux values. This consideration is supported by the fact that the sand particle size distribution during that period was distorted to that having particles larger than the normal conditions for the DOS. Thus, we excluded the biased data at and prior to 13:00 LST to derive the threshold speed in Fig. 4.

Figure 4 depicts the relationships of total saltation flux and the reciprocal of visibility with wind speed at 1.54 m. In general, the threshold speed (about 8−9 m s^{-1}) was almost the same in relation to both the saltation flux and visibility. The threshold wind speed u_t (m s^{-1}) for a saltation flux of particles ranging from 30 to 667 µm in diameter at the height of 0.06 m was determined with the following equation, which is similar to that proposed for threshold friction velocity by Owen (1964):

$$\textit{Saltation flux} = D \cdot u(u^2 - u_t^2) \quad (u \geq u_t), \tag{3}$$

where D is an empirical coefficient depending on sand particle size. For u_t, the value 8.9 m s^{-1} was obtained by the method of least squares. To compare this value with those obtained in other Asian regions, this value observed at 1.54 m was converted into the values of 10.4 and 11.9 m s^{-1} for heights of 3.8 and 10 m, respectively using Eq. (2). The first value at the DOS is larger than the value of 7.5 m s^{-1} for a gravel surface at 3.8 m height in the Taklimakan Desert (Mikami et al. 2005; Ishizuka et al. 2005). This value was observed at the sandy soil (0−10 mm depth) with a volumetric water content of 0.002 m^3 m^{-3}. The soil texture and water content are similar to those for our site. That is, the soil mainly consists of sand with few clay content (Table 1) and the soil water content measured by the oven dry method was 0.002 g g^{-1} (volumetric water content, about 0.003 m^3 m^{-3}) at 0−5 mm depth on 27 April.

The second value (11.9 m s^{-1}) is within the range of the SYNOP-estimated threshold speed for dust emission in northern Mongolia (9.8 ± 2.2 m s^{-1}) (Kurosaki and Mikami 2007), but it is higher than the SYNOP-estimated values for the Gobi and Taklimakan deserts. This comparison is possible because dust concentration (namely, dust emission) is proportional to saltation flux at our site (Kimura and Shinoda 2009).

3.2 Vegatation conditions

During the IOP, which was before the growing season, no green vegetation was seen, but some grazed vegetation with dead brown leaves remained from the previous year. The top soil was sandy and very dry (Table 1), and the roughness length was estimated as 0.0058 m from 45 northwesterly wind profile samples collected on 24 April. This estimate coincides fairly well with that estimated by the maximum correlation method (Mikami et al. 1996), which takes into account the effect of stability within the surface boundary layer. In the northwest part of the DOS, the vegetation cover and ground-observed NDVI were highly correlated (r^2 = 0.93). The vegetation cover and MODIS-estimated NDVI were 7.2% and 0.123, respectively, both satisfying conditions known to facilitate dust emission on the Loess Plateau (vegetation cover < 18% and NDVI < 0.2) (Kimura et al. 2009).

4. Conclusions

We conducted intensive observations of dust emission processes on the Mongolian steppe on 24 April 2008, prior to the growing season. The roughness length was 0.0058 m. The threshold speed at 1.54 m was 8.9 m s^{-1}, coinciding generally with the values estimated using SYNOP reports. Although the vegetation cover was very low (7.2%) and the grazed plant height was not high, the vegetation substantially raised the threshold speed for saltation. These results suggest that the vegetation produced in the summer of a given year and remaining through the succeeding cold grazing season may exert a carry-over effect on spring dust emissions. Such a vegetation memory was evidenced for this site by Shinoda et al. (2010) and for the other world's arid regions by several ecological studies.

Table 1. Width fraction* and topsoil characteristics (10 cm depth) northwest of the DOS.

	Width Fraction	Soil texture %			Soil chemical properties				
		Clay (< 0.002 mm)	Silt (0.002−0.02 mm)	Sand (0.02−2 mm)	pH (H_2O)	Electric conductivity (dS m^{-1})	Total nitrogen (%)	Available P_2O_5 (μg 100 g^{-1} dry soil)	C/N (%)
Mean	0.10	1.3	0.6	98.1	6.4	0.046	0.16	0.23	4.9
s.d.	0.11	0.1	0.1	0.1	0.4	0.008	0.02	0.13	0.8

*The fraction of the width of the remnant plant stand after grazing to a given length perpendicular to the DOS (i.e., projected into the prevailing wind direction). When the remnant was covered by sand, the surface soil was removed to measure the width. The survey was carried out at 10, 50, 150, and 300 m away from the DOS, and at each survey point the ratio was determined within a 1 m × 1 m plot. C/N denotes the ratio of carbon to nitrogen.

In particular, the three-year continuous severe droughts preceded the 2008 spring at this site (Section 2.1), most likely impacting the spring vegetation not only quantitatively (such as in phytomass) but also qualitatively (such as in species composition). In addition, soil moisture (including snowmelt water) memory may be another potential factor having the carry-over effect in the cold, arid region such as Mongolia (Shinoda 2001; Shinoda 2005). For future application, the concept of vegetation and soil moisture memory presented here will provide a useful basis for an early warning system of dust emission (e.g., Kimura and Shinoda 2009).

In this paper, we just claimed that the above threshold speed occurred on a certain vegetation state during the IOP, being larger than those observed previously in the deserts. In our future study, the threshold speed is expected to be expressed quantitatively as a function of various land-surface parameters. This requires repeated observations with different land-surface conditions that are carried out in the ongoing project (e.g., Kimura and Shinoda 2009).

Acknowledgments

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Supplements

1. Figure S1. Natural regions in Mongolia (Yunatov 1976*) and location of the study site (Bayan Unjuul) (star).
 * Yunatov, A. A., 1976. Fundamental characteristics of the vegetation of Mongolian People's Republic. Mongolian Academy of Science, Ulaanbaatar. (in Mongolian)
2. Table S1. Measurement parameters and instruments used for meteorological and dust observations at the DOS.

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