Effects of Soil and Land Surface Conditions in Summer on Dust Outbreaks in the Following Spring in a Mongolian Grassland

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Abstract

We propose an index of soil and land surface conditions for wind erosion to investigate their effects on dust outbreaks. The index is the normalized dust outbreak frequency (Nf_{DO}), which is the ratio of dust outbreak frequency to strong wind frequency. Nf_{DO} for April was always low in Mandalgobi, Mongolia, when the accumulated precipitation amount for June to August ($\mathrm{Prec}_{\mathrm{Jun-Aug}}$), soil moisture averaged for June to August ($\mathrm{SM}_{\mathrm{Jun-Aug}}$), and aboveground biomass for August ($\mathrm{AGB}_{\mathrm{Aug}}$) of the previous year exceeded their thresholds (100 mm, 13 mm, and $2.2*10^{-2}$ kg m^{-2}, respectively). This suggests that dead leaves of grasses in spring, which are the residues of vegetation from the preceding summer, suppress dust outbreaks. However, when $\mathrm{Prec}_{\mathrm{Jun-Aug}}$, $\mathrm{SM}_{\mathrm{Jun-Aug}}$, and $\mathrm{AGB}_{\mathrm{Aug}}$ are lower than the thresholds, Nf_{DO} varies over a wide range. This implies that when there are few dead leaves in spring, other possible factors after summer such as liquid precipitation leading to soil freezing, snow cover, melted water, and grazing, affect erodibility in spring. These results suggest that changes in soil and land surface conditions, rather than in wind conditions, chiefly affect the increased frequency of dust outbreaks. This dead-leaf hypothesis can be used as an early warning of dust-storm hazards.

1. Introduction

Wind erosion and the resulting aeolian dust have manifold effects such as on agriculture, grazing, transportation, human and animal health, and the climate. Clarifying the mechanism of dust emission and better recognition of the spatial and temporal distribution of the emission amount are important in developing countermeasures for desertification and improving the accuracy of numerical dust models.

The frequency of dust outbreaks, which are injections of soil particles from the surface to the atmosphere, as observed at World Meteorological Organization (WMO) synoptic stations (Kurosaki and Mikami 2003), increased in East Asia, especially in the Mongolian grasslands, from the 1990s to 2000s (Kurosaki et al. 2011). From observations of atmospheric anthropogenic radionuclides included in the deposition of dust particles in Tsukuba, Japan, Igarashi et al. (2009) also point out a possible shift of the dust source from the arid zone to the desert-steppe zone (including the Mongolian grasslands), which suffered from desertification during the 2000s.

Kurosaki et al. (2011) demonstrated that changes in erodibility, which is the susceptibility of soil and land surface to wind erosion (i.e., soil and land surface conditions), rather than changes in erosivity, which is the ability of wind to cause erosion (i.e., surface wind conditions), led to the increase in dust outbreaks in the Mongolian grasslands from the 1990s to 2000s. They demonstrated that the fifth percentile of threshold wind speeds ($u_{t5\%}$), where threshold wind speed is the minimum wind speed that required to cause a dust outbreak, became lower in the 2000s. This suggests that soil and land surface conditions were more vulnerable to dust outbreaks in the 2000s than in the 1990s. A drying trend—evident in an analysis of the Palmer Drought Severity Index (PDSI) (Dai et al. 2004; Dai 2010), reduced precipitation, greater potential evapotranspiration owing to increased air temperature, and reduced normalized difference vegetation index (NDVI) in the 2000s (Lotsch 2005; Nandintsetseg et al. 2010; Kurosaki et al. 2011)—supports the demonstrated reduction in threshold wind speed in Mongolia.

Field observations carried out by Shinoda et al. (2010) in Bayan Unjuul, located in the Mongolian steppe, showed that dead leaves of grasses (hereafter, dead leaves) in spring, which are the residues of vegetation from the previous summer, increase the threshold wind speed.

In this paper, we present interannual variations in the dust outbreak frequency (f_{DO}) and strong wind frequency ($f_{u>ut5\%|\mathrm{Apr}}$) in April, and we elucidate the relationship between erosivity and dust outbreaks from this result. We also show the interannual variation in the erodibility condition using the normalized dust outbreak frequency (Nf_{DO}). This index is useful for expressing the yearly condition of erodibility, as explained in Section 2.4. Moreover, we present details relating to precipitation, soil moisture, aboveground biomass (AGB), and NDVI in summer, and we discuss the effect of such erodibility factors on dust outbreaks in April of the following year.

2. Data and method

2.1 Study site

Our study site was a synoptic meteorological station in Mandalgobi (45.767°N, 106.283°E, 1393 m above sea level) registered with the WMO. The station is located in the desert-steppe zone, which is close to the steppe zone, in Mongolia (Fig. 1).

2.2 Surface observation data

We used the present weather, wind speed, air temperature, precipitation amount, and snow depth included among the synoptic surface observation data archived at the Institute of Meteorology and Hydrology (IMH) of Mongolia, Meteorological Research Institute of Japan, and National Climatic Data Center of the United States for 1969 to 2009, though there were gaps in the data for some years. The observation intervals for snow depth, precipitation amount, and the others are basically for 24 hours (00 UTC), 12 hours (00 and 12 UTC), and 3 hours (00, 03, …, and 21 UTC), respectively.

Present weather data was used to detect dust outbreaks, which is a category of present weather indicating the injection of soil particles from the surface to the atmosphere (Kurosaki and Mikami 2003). The category includes dust or sand raised by wind (ww = 07), dust or sand whirls (ww = 08), and dust or sand storms (ww = 09, 30−35, 98) at or near the station (WMO 1995). Widespread dust in suspension in the air (ww = 06) was excluded from the category of dust outbreak. Wind-speed data was used in calculations of $u_{t5\%}$ and $f_{u>ut5\%|\mathrm{Apr}}$. The method to estimate $u_{t5\%}$ was the same as that in Kurosaki and Mikami (2007), and $u_{t5\%}$ for April from 1970 to 2009 ($u_{t5\%|\mathrm{Apr}}$ = 13.1 m s^{-1}) was employed as the threshold for strong wind. We calculated the accumulated precipitation amount for June to August ($\mathrm{Prec}_{\mathrm{Jun-Aug}}$) as the precipitation amount for the major plant-growing season in the Mongolian grasslands (Shinoda et al. 2007; Nandintsetseg et al. 2010). The precipitation data was

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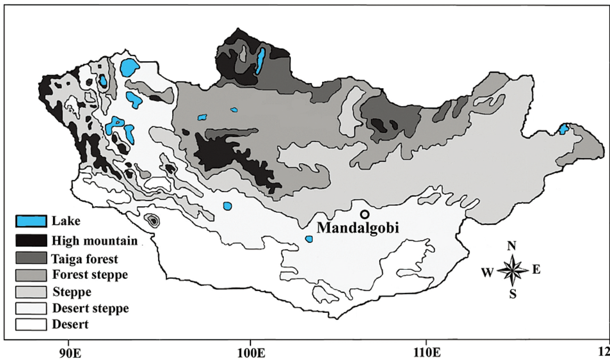

Fig. 1. Location of Mandalgobi and vegetation zones in Mongolia.

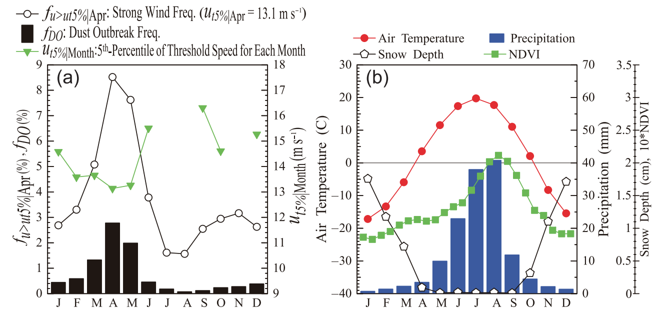

Fig. 2. Seasonal variations of $f_{u>ut5\%|\mathrm{Apr}}$ (open circles), f_{DO} (bar chart), and $u_{t5\%}$ (green inverted triangles) in (a), and air temperature (red circles), precipitation amount (blue bar chart), snow depth (open pentagons), and NDVI (green squares) in (b). $u_{t5\%|\mathrm{Month}}$ signifies $u_{t5\%}$ for each month.

also used in estimating three months' average of soil moisture of the 0−50 cm depth for June to August ($SM_{Jun-Aug}$) with air temperature data. Soil moisture was calculated by the one-layer water balance model (Nandintsetseg and Shinoda 2010) for the period 1969−2006. AGB data for the period 1986−2005 was provided by IMH. AGB observations were made in a fenced pasture, representing the naturally occurring species above ground, and they were conducted on the 4th, 14th, and 24th of each month from May to September. We employed the maximum in August (AGB_{Aug}) as a representative of AGB during the peak growing season.

2.3 NDVI data

We used the bimonthly 8-km resolution NDVI dataset of Global Inventory Modeling and Mapping Studies (GIMMS) (Tucker et al. 2004) for the period from August 1981 to December 2006. We employed the annual maximum NDVI ($NDVI_{max}$) as it is representing the annual peak amount of above-ground vegetation. In the case of 1981, we employed the maximum for August to December.

2.4 Normalized dust outbreak frequency (Nf_{DO})

The occurrence of a dust outbreak depends on the interrelationship of the erosivity factor (i.e., wind speed) and erodibility factors (i.e., soil and land surface conditions). Since erosivity includes only one factor, we can measure it by wind speed alone. However, erodibility consists of a variety of factors, such as soil-particle size distribution, soil moisture, vegetation coverage, soil crust, snow cover, soil freeze, and land use. Moreover, these factors are not always independent of each other. Threshold wind speed can be regarded as a unified index of a variety of erodibility factors. However, in estimating $u_{t5\%}$, we need an observation period of several to 10 years to obtain sufficient samples. Thus, $u_{t5\%}$ cannot show year-to-year variation of erodibility.

As an erodibility index that can reflect year-to-year variation, we employed Nf_{DO}, which is dust outbreak frequency normalized by strong wind frequency:

$$Nf_{DO} = f_{DO} / f_{u>ut5\%|\mathrm{Apr}}. \quad (1)$$

High/low Nf_{DO} suggests high/low erodibility, which signifies vulnerable/hard soil and land surface conditions to dust outbreaks. This index is the same as the dust outbreak ratio in Kimura et al. (2009), which is also the ratio of dust outbreak frequency to strong wind frequency, but the difference is that they employed 7.0 m s^{-1} as the threshold of strong wind.

3. Results and discussion

3.1 Seasonal variation

Figure 2a shows seasonal variations of $f_{u>ut5\%|\mathrm{Apr}}$, f_{DO}, and $u_{t5\%}$ in Mandalgobi, while Fig. 2b presents surface air temperature, precipitation amount, snow depth, and NDVI. From Fig. 2a, it is evident that $u_{t5\%}$ is lowest in April, although the values are not presented for some months, when wind speeds were consistently lower than the threshold wind speeds. The lowest $u_{t5\%}$ would suggest that soil and land surface conditions are most vulnerable to dust outbreaks in April. In reality, the low NDVI in April indicates that this is the month before the appearance of new vegetation (Fig. 2b). Almost 0-cm snow depth and above-0°C air temperatures suggest virtually no snow cover and no soil freezing in April. These may have led to the lowest threshold wind speed. The combination of the lowest $u_{t5\%}$ and highest $f_{u>ut5\%|\mathrm{Apr}}$ produces the highest f_{DO}. Since we can expect a low effect of new vegetation, snow cover, and soil freezing on dust outbreaks in April, as noted above, we can also expect a high effect of dead leaves, as discussed in Shinoda et al. (2010).

3.2 Interannual variation

Figure 3a shows interannual variations of $f_{u>ut5\%|\mathrm{Apr}}$, f_{DO}, and Nf_{DO}, and Fig. 3b shows those of $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, AGB_{Aug}, and $NDVI_{max}$. $f_{u>ut5\%|\mathrm{Apr}}$ presents a decreasing trend into the mid-1990s; since then there has been little overall change although the year-by-year variation is great. f_{DO} shows a decreasing trend for 1970−2000, but it suddenly increases in 2001, and high f_{DO}s were often found after that year. Nf_{DO} demonstrates a slightly decreasing trend for 1970 to the mid-1990s, but it has rapidly increased since the mid-1990s.

$Prec_{Jun-Aug}$ shows a decreasing trend for the mid-1970s to late 1980s, an increasing trend until the mid-1990s, and a decreasing trend until 2008. $SM_{Jun-Aug}$ is almost one-tenth of $Prec_{Jun-Aug}$, and their interannual variations are very similar, with the correlation coefficient and p-value being r = 0.906 and p < 0.0001, respectively. AGB_{Aug} shows a similar interannual variation with those of $Prec_{Jun-Aug}$ and $SM_{Jun-Aug}$. AGB_{Aug} displays an increasing trend for the mid-1980s to mid-1990s and a decreasing trend until the mid-2000s. The correlation of AGB_{Aug} with $Prec_{Jun-Aug}$ is high (r = 0.721, p < 0.001). $NDVI_{max}$ shows an increasing trend for 1981 to the early 1990s and a decreasing trend until 2006. This tendency is similar to those of $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, and AGB_{Aug}. However, we could not find a significant correlation (e.g., r = 0.360 and p = 0.07 in the case of $Prec_{Jun-Aug}$). The decreasing trends of $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, AGB_{Aug}, and $NDVI_{max}$ since the mid-1990s may have caused the rapidly increasing trend of Nf_{DO} since the mid-1990s, resulting in frequent dust outbreaks since 2001.

A correlative relationship was not found between $f_{u>ut5\%|\mathrm{Apr}}$ and f_{DO} for 1970 to 2009 (r = 0.176, p = 0.285; figures not shown). This result agrees with that of Kurosaki and Mikami (2005), who demonstrated no correlation between strong wind frequency, where strong wind was defined as a wind speed of 6.5 m s^{-1}, and f_{DO} in the Mongolian grasslands. These results suggest that erodibility factors (i.e., soil and land surface conditions), rather than the erosivity factor (i.e., wind speed condition), chiefly affect dust outbreaks in April in their interannual variation.

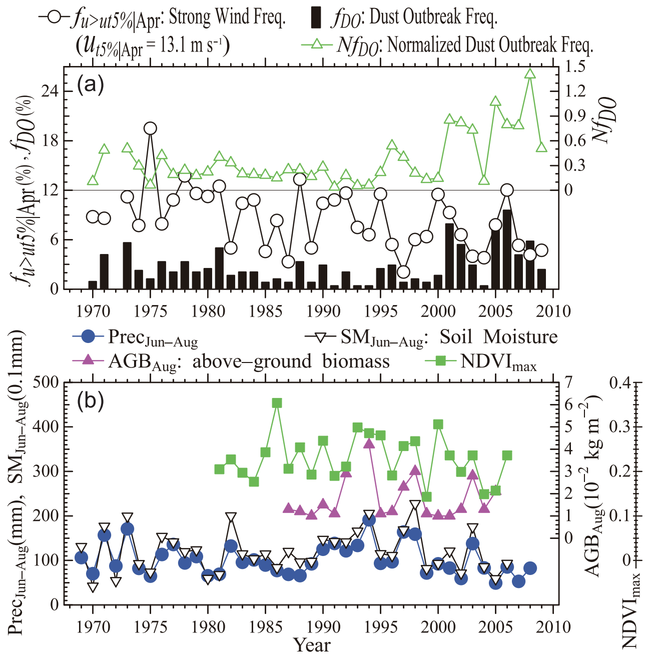

Fig. 3. Interannual variations of $f_{u>ut5\%|Apr}$ (open circles), f_{DO} (bar chart), and Nf_{DO} (green open triangles) in (a), and Prec$_{Jun-Aug}$ (blue circles), SM$_{Jun-Aug}$ (open inverted triangles), AGB$_{Aug}$ (purple triangles), and NDVI$_{max}$ (green squares) in (b).

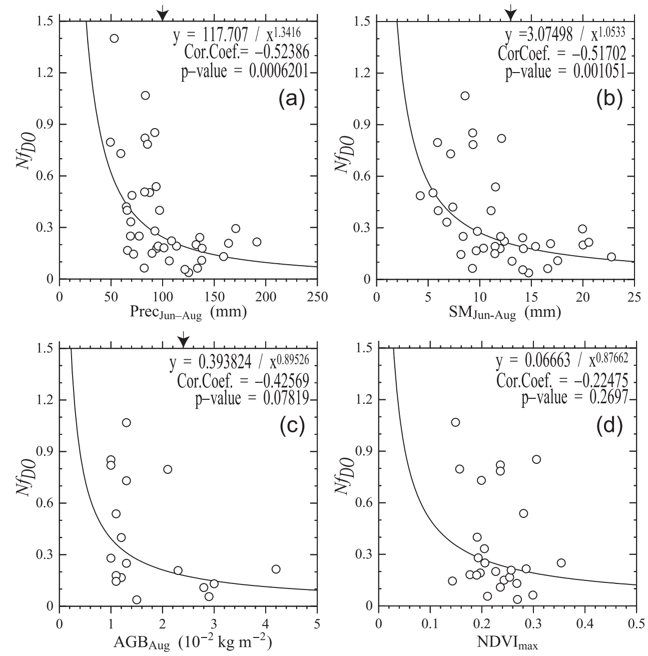

Fig. 4. Scatter diagrams for soil and land surface conditions in summer (a, Prec$_{Jun-Aug}$; b, SM$_{Jun-Aug}$; c, AGB$_{Aug}$; and d, NDVI$_{max}$) and Nf_{DO} in April of the following year. The arrow in (a)−(c) indicates the approximate threshold that leads to low erodibility (i.e., low Nf_{DO}) in April of the following year.

The panels in Fig. 4 show the relationship between (a) Prec$_{Jun-Aug}$, (b) SM$_{Jun-Aug}$, (c) AGB$_{Aug}$, and (d) NDVI$_{max}$ and Nf_{DO}. The plots have an L-shaped distribution for Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$. When these three variables exceed certain thresholds, Nf_{DO} is low. On the other hand, when the three variables are below the thresholds, Nf_{DO} varies over a wide range. The thresholds are about 100 mm, 13 mm, and $2.2*10^{-2}$ kg m^{-2} for Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$, respectively.

The distributions of the plots in the three variables also appear like a function of $y = a/x^b$. We obtained regression curves and correlation coefficients using a linearized function, $\ln(y) = \ln(a) - b * \ln(x)$. Significant negative correlations with Nf_{DO} are found in Prec$_{Jun-Aug}$ ($r = -0.527$, $p < 0.001$) and SM$_{Jun-Aug}$ ($r = -0.517$, $p = 0.001$). A negative correlation with Nf_{DO} is also found in AGB$_{Aug}$, but this is not significant ($r = -0.426$, $p = 0.078$). We consider this low correlation has possibly been caused by reduced accuracy in AGB observation in cases of low AGB. We find neither an L-shaped distribution nor a correlative relationship between NDVI$_{max}$ and Nf_{DO}. Possible reasons for this result and low correlations of NDVI$_{max}$ with Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$ are effects of human activities such as grazing, changes in vegetation species owing to climatic change and/or overgrazing, scale gap between pixel size of NDVI (8 km) and spatial scale of dust outbreaks (unknown), and accuracy in location information at the meteorological station.

Kurosaki et al. (2011) proposed a hypothesis that dead leaves in spring are the primary erodibility factor (hereafter, the dead-leaf hypothesis). In this hypothesis, the precipitation amount during the vegetation growing season predominantly controls plant production in summer, the vegetation in summer remains as dead leaves until spring in the following year, and consequently the dead leaves chiefly control the erodibility in spring. If the dead-leaf hypothesis is valid, when Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$ are high/low, Nf_{DO} would always have to be low/high. In reality, our results show that when Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$ exceed the thresholds, Nf_{DO} is always low. This suggests that the dead-leaf hypothesis is applicable in cases of high Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$; we can regard significant precipitation and soil moisture in summer as giving rise to considerable vegetation growth in summer, resulting in low erodibility (i.e., high threshold wind speed and low Nf_{DO}) owing to substantial amounts of dead leaves in the following spring. In such a case in spring, even when $f_{u>ut5\%|Apr}$ is high, f_{DO} would tend to be low.

However, when Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$ are low, the hypothesis is not always applicable. Our results show that when Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGBAug are below the thresholds, Nf_{DO} has values over a wide range. Possible reasons are liquid precipitation leading to soil freezing, snow cover, melted water, and grazing from fall to spring. If snow cover, soil freezing, melted water, and dead leaves are not present in spring, we can expect high Nf_{DO}. However, if at least one of these is found in spring, even when the amount of dead leaves is small, we can expect low Nf_{DO}.

We propose an application of the results obtained in this paper for an empirical forecasting of dust outbreaks as an early warning system. The combination of Nf_{DO} obtained from Prec$_{Jun-Aug}$, SM$_{Jun-Aug}$, and AGB$_{Aug}$ in the previous year and forecasted wind speed by numerical models provides us with the probability of dust outbreaks. Even if we have no information about wind, when the three variables are lower than their thresholds (e.g., Prec$_{Jun-Aug}$ < 100 mm), we can determine whether there is a high risk of a dust-storm hazard in the following April in Mandalgobi.

4. Summary

We investigated the effects of erosivity (i.e., wind conditions) and erodibility (i.e., soil and land surface conditions) on dust outbreaks in Mandalgobi, Mongolia, by an analysis of $f_{u>ut5\%|Apr}$ and f_{DO}. The low correlation between these frequencies in April suggests that the chief causes in the interannual variation in dust outbreaks lie in erodibility.

To examine erodibility, we proposed Nf_{DO}, which is the ratio of f_{DO} and $f_{u>ut5\%|Apr}$, as an index of erodibility. Nf_{DO} has rapidly increased since the mid-1990s, and this suggests that soil and land surface conditions have become more vulnerable to dust outbreaks year by year. Since wind conditions showed no noticeable trend

over this period, we can regard changes in erodibility factors as having led to the high frequency of dust outbreaks in the 2000s. Referring to the dead-leaf hypothesis, we examined the effects of $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, AGB_{Aug}, and $NDVI_{max}$ on erodibility in April of the following year. We obtained the result that when $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, and AGB_{Aug} exceed the thresholds (100 mm, 13 mm, and $2.2*10^{-2}$ kg m^{-2}, respectively), Nf_{DO} is low; in cases where these are below the thresholds, Nf_{DO} has values over a wide range. This suggests that when the three variables are high, the dead-leaf hypothesis is applicable (i.e., dead leaves suppress dust outbreaks). However, when the three variables are low, we can expect few dead leaves in the following spring; possible factors here are liquid precipitation leading to soil freezing, snow cover, melted water, and grazing from fall to spring affecting the erodibility (threshold wind speed and Nf_{DO}) in spring.

We proposed an application of the relationships of $Prec_{Jun-Aug}$, $SM_{Jun-Aug}$, and AGBAug with Nf_{DO} for an empirical forecasting of dust outbreaks in April as an early warning system. We obtained the probability of dust outbreaks from a combination of Nf_{DO} derived from the three variables and forecasted wind speed. Even when there is no information about wind, this system provides an advance warning of a high risk of dust-storm hazards when the three variables are lower than the thresholds (e.g., $Prec_{Jun-Aug} <$ 100 mm) in Mandalgobi.

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