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Effects of soil moisture on dust emission from 2011 to 2015 observed over the Horqin Sandy Land area, China

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ABSTRACT

Using the observational data of dust concentrations and meteorological parameters from 2011 to 2015, the effects of soil moisture and air humidity on dust emission were studied at long (monthly) and short (several days or hours) time scales over the Horqin Sandy Land area, Inner Mongolia of China. The results show that the monthly mean dust concentrations and dust fluxes within the near-surface layer had no obvious relationship with the monthly mean soil moisture content but had a slightly negative correlation with monthly mean air relative humidity from 2011 to 2015. The daily mean soil moisture exhibited a significantly negative correlation with the daily mean dust concentrations and dust fluxes, as soil moisture changed obviously. However, such negative correlation between soil moisture and dust emission disappeared on dust blowing days. Additionally, the effect of soil moisture on an important parameter for dust emission, the threshold friction velocity (u_{*t}), was investigated during several saltation-bombardment and/or aggregation-disintegration dust emission (SADE) events. Under dry soil conditions, the values of u_{*t} were not influenced by soil moisture content; however, when the soil moisture content was high, the values of u_{*t} increased with increasing soil moisture content.

1. Introduction

Mineral dust aerosols generated from dust emission in arid and semi-arid regions affect the Earth system through many physical, chemical and biological processes, such as scattering and absorption radiation in the atmosphere (Huang et al., 2006; DeMott et al., 2010; Mather et al., 2010; Shao et al., 2011), modifying cloud optical properties (Huang et al., 2006; DeMott et al., 2010), changing snow and ice surface albedo (Painter et al., 2010; Shao et al., 2011), providing nutrients to ecosystems (Mahowald et al., 2009, 2010; Mather et al., 2010) and influencing the carbon exchange between the atmosphere and sea (Mahowald et al., 2010; Mather et al., 2010; Shao et al., 2011). Moreover, large loads of dust aerosols usually cause very low atmospheric visibility and are threats to human health (Csavina et al., 2011; Degobbi et al., 2011; Morman and Plumlee, 2013).

The physics of dust emission is very complex, as it involves atmospheric, soil, and land surface processes (Shao and Lu, 2000). Dust particles can be removed from the soil surface and released to the atmosphere under the conditions of $u_* > u_{*t}$, where u_* is friction velocity that is a parameter used to describe the shear stress exerted on the surface by wind shear, and u_{*t} is threshold friction velocity that is the minimum friction velocity that is required to initiate movement of an aggregate or particle resting on the soil surface (Gillette et al., 1998; Alfaro and Gomes, 2001, Li et al., 2010). Parameter u_* is determined by winds aloft and surface roughness (Sharratt and Vaddella, 2012), while u_{*t} is mainly affected by land surface characteristics, including soil texture (Belnap and Gillette, 1998), surface soil moisture content (Ishizuka et al., 2005), soil particle size distribution (Gillette et al., 1980), vegetation cover (Kimura and Shinoda, 2010) snow cover (Kurosaki and Mikami, 2004), and soil crust (Sharratt and Vaddella, 2014). The determination of u_{*t} over different sand sources is very important, because it is widely used to estimate dust emission flux in dust models (Sundram et al., 2004; Zhu and Zhang, 2010; Kang et al., 2011; Li and Zhang, 2011; Kok et al., 2014; Xi and Sokolik, 2015) and is one of the important criteria to distinguish CTDE (convective turbulent dust emission) and SADE (saltation-bombardment and/or aggregation-disintegration dust emission) events (Li et al., 2014; Li and Zhang, 2015). However, the values of u_{*t} during different seasons and years are difficult to accurately estimate, mainly due to rare long-term observational data from field experiments.

As an important influencing factor of u_{*t} (Cornelis et al., 2004; Feng and Sharratt, 2005; Zhang et al., 2012), the relationship between soil

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moisture and dust emission has been studied through wind-tunnel and field experiments (Chepil, 1956; McKenna-Neuman and Nickling, 1989; Chen et al., 1996; Cornelis and Gabriels, 2003; Cornelis et al., 2004; Pierre et al., 2012). Or and Tuller (1999) indicated that capillary force was negligible with matric potential $\Psi < -10$ M Pa but influenced inter-particle forces as $\Psi > -10$ M Pa. However, Sharratt et al. (2013) showed that soil moisture content had no influence on u_{*t} when Ψ was beyond the range of -25 to -1 MPa, and u_{*t} increased sharply with an increase in Ψ above -1 MPa. McKenna-Neuman (2003) indicated that the effect of matric potential of the adsorbed water on u_{*t} was not obvious when Ψ was not extremely high, which was consistent with the results of Sharratt and Vaddella (2012).

Based on the previous results from wind-tunnel experiments, many theoretical models have been developed to express threshold friction velocity as a function of soil moisture content and air relative humidity (McKenna-Neuman and Nickling, 1989; Cornelis et al., 2004; Wang, 2006; Dong et al., 2007). Many previous studies also reported that threshold friction velocity u_{*t} is influenced by air humidity through the soil moisture (Gregory and Darwish, 1990; Darwish, 1991; McKenna-Neuman, 2003; Ravi et al., 2004; Zhang et al., 2012; Csavina et al., 2014). Ravi et al. (2004) investigated the dependence of u_{*t} on air humidity in air-dry soils based on wind-tunnel experiment s and found that in some case an increase in air humidity will result in a decrease in u_{*t}. Ravi et al. (2006) conducted a series of wind tunnel experiments and theoretical analyses and indicated that when the value of air relative humidity falls in the range of 40% and 65%, the u_{*t} decreases with an increase in relative humidity, while above or below this range, u_{*t} increases with air humidity. However, these studies didn't consider the effects of time scale on the relationship between soil moisture or air humidity and u_{*t}. Li and Zhang (2014) observed that large soil moisture increased the values of u_{*t} and suppressed the dust emission process over the Horqin Sandy Land area, for given individual SADE events; however, Li and Zhang (2014) also indicated the relationship between soil moisture and dust emission was not obvious on a monthly time scale at the same sandy area.

As an important parameter in the dust emission models (Sundram et al., 2004; Zhu and Zhang, 2010; Kang et al., 2011; Shao et al., 2011; Kok et al., 2014; Xi and Sokolik, 2015), u_{*t} is difficult to determine. As an important influencing factor of u_{*t} (Cornelis et al., 2004; Feng and Sharratt, 2005; Zhang et al., 2012), more field research is required to investigate the relationship between soil moisture and dust emission.

Based on the dataset of micrometeorological parameters, soil moisture content, and dust concentrations obtained from a sandstorm monitoring station in the Horqin Sandy Land area from 2011 to 2015, effects of soil moisture on dust emission over different time scales were investigated in this study.

2. Experiment and methods

2.1. Experiments in the Horqin Sandy Land

The field experimental site was located at the Horqin Sandy Land (42°56′N,120°42′E) which was severely damaged by overgrazing and overcutting since Qing dynasty in Naiman County of Inner Mongolia, China. The annual mean precipitation is approximately 366 mm and the mean annual potential evaporation is 1936 mm (Wang et al., 2013) which means it is classified as a semi-arid region. The landscape of the Horqin site is gently undulating and dominated by shifting, semi-shifting, and fixed dunes. The vegetation surrounding the experiment site largely consists of low, open shrubs (Zhao et al., 2007, Park and Park, 2014).

A 20-m observational tower was built at the Horqin site in 2007. The observations included (1) micrometeorological parameters: wind speed (010C, Met One Instruments Inc.) at heights of 2, 4, 16, and 20 m; wind direction (020C, Met One Instruments Inc.) at a 20 m height; air temperature and humidity (HMP45C, Campbell Sci. Inc.) at heights of 2, 4, 8, and 16 m; shortwave radiation (LI200X, Li-Cor Co.), net radiation (NR-Lite, Kipp&Zonen) at a 2 m height and shortwave radiation and longwave radiation (CNR4, Kipp&Zonen) which is installed in 2015 still at a 2 m height; precipitation (52202, R. M. Young Co.), and air pressure (PTB110, Vaisala Co.) at the surface; (2) soil parameters: soil temperature (CS107, Campbell Sci. Inc.) and soil moisture content (CS616, Campbell Sci. Inc.) at depths of 5, 20, and 50 cm under the surface; and (3) dust parameters: dust (PM10) mass concentration measured by beta-gauges (FH62-C14, Thermo Co.) at heights of 3 and 18 m (Li and Zhang, 2011, 2012, 2014; Li et al., 2014; Park et al., 2011).

The measurements at the Horqin site were recorded automatically and continuously with a 10-min sampling frequency and 30-min moving averages were derived from the raw data (Zhang et al., 2008). Raw data was then processed to derive various variable values relevant for dust inter-comparison. The detailed information of how to deal with the data is as follows:

2.2. Calculation of velocity scales and vertical dust flux

Friction velocity (u_*) is an important parameter in dust emission studies that used represents the shear stress and was calculated with wind speed and air temperature profiles based on the Monin–Obukhov similarity theory (Garratt, 1992):

$$u_* = \kappa \overline{U}(z)\left[\ln\left(\frac{z-d}{z_0}\right) - \Psi_m\left(\frac{z-d}{L}\right) + \Psi_m\left(\frac{z_0-d}{L}\right)\right]^{-1} \quad (1)$$

where κ = 0.4 is the von Karman's constant; $\overline{U}(z)$ is the mean of the wind speeds at heights of 4 and 16 m (therefore, z = 10 m is the reference level and the observational height); z_0 (unit: m) is the roughness length and can be calculated by plotting $\kappa U/u_*$ against the stability factor z/L under stable (z/L > 0) and unstable (z/L < 0) conditions (Li and Zhang, 2012). The value of z_0 also depends on vegetation cover which varied from month to month. Moreover, the underlying surface surrounding the Horqin station is not completely flat and uniform, the values of z_0 were calculated in different months and wind directions. The values of z_0 in different months and under different wind direction from 2011 to 2015 were listed in Table 1. d (unit: m) is the displacement height and can be regarded as zero in this study because the value at the Horqin site was much smaller than the z and z_0 values; L is the

Table 1
The statistical results of z_0 (unit: m) during different month and wind direction from 2011 to 2015.

Month	0°–45°	45°–90°	90°–180	180°–225°	225°–270°	270°–315°	315°–360°
January	0.028	0.05	0.04	0.043	0.013	0.005	0.018
February	0.009	0.05	0.04	0.043	0.013	0.005	0.018
March-April	0.009	0.38	0.04	0.043	0.006	0.005	0.018
May-June	0.028	0.15	0.04	0.043	0.006	0.005	0.018
July-August	0.028	0.15	0.04	0.124	0.006	0.005	0.034
September	0.028	0.15	0.04	0.124	0.013	0.005	0.034
October-November	0.028	0.05	0.04	0.088	0.013	0.005	0.034
December	0.028	0.05	0.04	0.088	0.013	0.005	0.018