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Observation and modeling of black soil wind-blown erosion from cropland in Northeastern China

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ABSTRACT

As the nation's bread basket, Northeastern China has experienced dramatic land use changes in the past decades, with much natural land being converted into cropland to feed the growing population. The long dormant season, coupled with frequent cold fronts and strong spring winds, makes the exposed cropland vulnerable to wind erosion. However, the rates and spatial–temporal characteristics of wind erosion in this particular soil type have been poorly studied. The present study aimed to measure and simulated the wind erosion characteristics from black soil cropland in the Dehui region of Northeastern China. Our results showed that wind-blown erosion was positively correlated with wind speed and negatively linked to soil moisture, vegetation and soil roughness in this region. The measured threshold friction velocity was 4.47 m/s at 2 m height, corresponding to 0.37 m/s at the surface ground. Based on WRF-CMAQ-FENGSHA model, we localized the parameters and simulated a significant wind erosion event in the Dehui region on May 31, 2013. The relationships between modeled dust flux and ground measurement were correlated (R^2 = 0.78). In addition, the modeled aerosol optical depths were also captured by satellite observations (MODIS and CALIPSO). Our results indicate that the bare farmland areas over Northeastern China are important dust sources over this region, and should not be neglected in regional air quality models. The use of protective farming techniques, protection of grassland and plowing in autumn for cropland areas should be considered to combat dust emission.

1. Introduction

A crucial criterion for the existence of wind erosion is the availability of fine particles which can be lifted from the ground when surface wind velocity exceeds a certain threshold wind speed. The wind erosion decreases soil texture, nutrient content, vegetation growth and productivity (Chameides et al., 1999); it effects atmospheric visibility and climate change (Chen et al., 2014), transports micro-nutrients to terrestrial and marine ecosystems (Quinton et al., 2010), and even endangers human health (Goudie, 2014). The wind-blown dust which generally arises from natural processes is commonly at severe levels in arid or semi-arid areas (e.g. desert, Gobi and alluvial deposits), but agricultural activities that disturb the soil can greatly increase the frequency and amount of wind-blown dust (Zender et al., 2004; Engelstaedter et al., 2006; Ginoux et al., 2012). Wind-blown erosion from cultivated and grazed soils is a global problem that has inspired studies in North America (Saxton et al., 2000; Nordstrom and Hotta, 2004; Singh et al., 2012), South America (Mendez and Buschiazzo, 2010), Africa (Toure et al., 2011; Wiggs and Holmes, 2011), Europe (Gomes et al., 2003a,b; Borrelli et al., 2014), Asia (Li et al., 2004; Guo et al., 2013; Wang et al., 2013) and Australia (Webb et al., 2006; Harper et al., 2010; Chappell et al., 2014).

Only a few studies have attempted to estimate the contribution of anthropogenic sources to global dust emission by comparing scenarios in numerical dust models with ground-based observations as well as satellite products (Tegen and Fung, 1995; Sokolik and Toon, 1996; Tegen et al., 2004; Park et al., 2010; Ginoux et al., 2012). Ginoux et al. (2012) have estimated that wind erosion and transport from cropland contribute approximately 25% of the total amount of atmospheric dust (Ginoux et al., 2012); however, these processes are important to humans as they occur in inhabited areas, where human health and soil fertility are adversely affected by enhanced dust emissions. Anthropogenic dust sources are associated with land use, and thus, field measurements are essential to further understand wind-erosion processes from cropland and verify wind-erosion models, but there are very few studies relevant to wind-blown erosion of cropland in China (Li et al., 2004; Zhao et al., 2006; Chen et al., 2007).

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Land use changes must be considered in dust emission models (Tegen et al., 2004). Land cover in the Northeastern China dust source region includes grassland, dry river beds and lakes, salt lakes, croplands, and mines. Agricultural land and playas, and their margins, have been identified as focus areas for dust emission in the Chihuahuan Desert (Rivera Rivera et al., 2010). As the nation's bread basket, Northeastern China has experienced dramatic land use change in the past century, with much of the wild land being converted into cropland to feed a growing population (Wang et al., 2011; Zhao et al., 2014). The long cold season, coupled with frequent cold fronts and strong spring winds (Dickerson et al., 2007), makes the exposed cropland vulnerable to wind erosion (Fig. 10 in (Ginoux et al., 2012)). The loss of top soil caused by wind-blown erosion not only reduces soil productivity, but also degrades air quality and contributes to regional haze (Zhang et al., 2012). To understand, predict, and mitigate the impact of dust aerosol on air quality and climate, it is necessary to accurately parameterize the emission rate of dust particles in the wind erosion processes on croplands. However, windblown dust emission from croplands is poorly represented in existing air quality models.

The black soil in the Northeastern China is rich in organic carbons and crusts, which can dramatically alter the threshold wind velocity required to initiate wind erosion (Sharratt and Vaddella, 2014). The effects of such rich organic carbon content on the susceptibility of cropland to wind erosion are expressed as: (1) promotion of the formation of a surface crust, which acts to hold in soil moisture and resist erosion, and (2) significant aggregation, which impacts on aggregate disintegration and vertical dust flux. However, there is a lack of observation data on the parameterization of dust emission such as threshold wind speed, saltation flux, dust concentration, vegetation cover and soil properties in this area.

In this paper, we firstly report the field observations relevant to windblown erosion of cropland, and present the numerical modeling of a typical dust event sourced from black soil areas with consideration of the crust effects, in Northeastern China.

2. Observation and modeling methods

2.1. Experimental site

A wind-erosion monitoring study was initiated in the spring of 2013 at the Dehui Experimental Station (44° 12′N, 125°33′E) of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Jilin Province, China (Fig. 1). The observation site is located in the black soil area with a continental monsoon climate in Northeastern China. The mean annual temperature is 4.4 °C, and the mean annual precipitation is 520.3 mm, with more than 70% occurring in June, July and August. The studied soil is a black soil (Udolls, USDA Soil Taxonomy, or Black Chernozem, Canadian soil classification) with the texture of clay loam (Typic Hapludoll) containing 36% clay, 24% silt and 40% sand. The mean soil organic carbon content of the top soil is 1.65% (Liu et al., 2006a,b). More detailed physical and chemical properties were presented by (Liang et al., 2007). Prior to our observations, the land had been used for continuous maize production under conventional tillage management for more than 20 years (Fig. 1).

2.2. Instrumentation

This study was conducted from April to June, 2013. Only one dust storm event (May 31) was observed and analysed in detail. A 5 m instrument tower has been installed at the downwind edge of the selected cropland site. The tower provided a platform to measure the wind velocity profile (5 heights, 0.2 m, 0.5 m, 1.0 m, 2.0 m and 5.0 m, 010C, Met One Instruments Inc.), wind direction (instrument height 2.0 m, 020C, Met One Instruments Inc.), air temperature and relative humidity (instrument height 2.0 m, HMP45C, Campbell Sci. Inc.). Volumetric soil moisture content was measured with three amplitude domain reflectometry probes (CS616-L, Campbell Sci. Inc.) that were placed 2 m away and average around the tower. Saltating particles were detected with a SENSIT® (Model H11-LIN, Sensit, Co.) particle impact detector in the center of the field. The SENSIT uses a piezoelectric crystal to detect saltating sand grains at a frequency of 1 Hz and amplifies the signals 10× to increase the sensitivity. In this study, the piezoelectric crystal was mounted at 0.02 m above the soil surface. Instantaneous measurements were taken at intervals of 1 s for saltation, wind speed and direction and at 6 s for soil moisture, air temperature and humidity, and recorded by a data logger (CR1000, Campbell Scientific). Finally, all data were averaged over 1 min intervals. The whole monitoring system for wind-blown erosion was powered by solar panels and a colloidal battery. PM_{10} dust concentrations (mg m^{-3}) were measured using DustTrak® (Model 8520, TSI, Inc.) aerosol monitors mounted on the tower at 0.5 and 1.5 m height. The vertical flux was calculated according to the method described by Zobeck and Van Pelt (2006). The surface roughness of the soil was measured by the chain method (Saleh, 1993; Zobeck et al., 2003).

2.3. Numerical modeling

2.3.1. Model description and configuration

The U.S. EPA's Community Multi-scale Air Quality (CMAQ) modeling system (Byun and Schere, 2006) was adopted in this study. CMAQ is a three-dimensional Eulerian modeling system that can calculate the mass balance within each grid cell by solving the transport across each cell boundary and chemical transformations within each cell during a given time period. One-way double nesting simulation domains were used in this study, as shown in Fig. 1. Domain 1 covered the whole of East Asia with a horizontal grid resolution of 54 km × 54 km, and Domain 2 covered the Northeastern China with a grid resolution of 18 km × 18 km. All two-level domains used the same vertical domain set up with 14 vertical layers that reach approximately 20 km above the ground. The first layer thickness was approximately 38 m.

The Weather Research and Forecasting (WRF) version 3.2.1 was employed to generate the meteorological fields for CMAQ (Skamarock et al., 2005). The initial and boundary fields were obtained from final operational global analysis data of the National Center for Environmental Prediction (NCEP) with 1° × 1° resolution (available at http://rda.ucar.edu/datasets/ds083.2). The physical options used in the WRF model were WRF Double-Moment 6-class microphysics scheme (Lim and Hong, 2010), the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave and shortwave radiation scheme (Mlawer et al., 1997, 1998), Pleim–Xiu land surface scheme (Xiu and Pleim, 2001) ACM2 PBL scheme (Pleim, 2007), and Grell–Devenyi ensemble cumulus scheme (Grell and Dévényi, 2002). In this study, the INDEX-B inventory was employed as the anthropogenic emission inventory (Zhang et al., 2009).

2.3.2. Windblown dust module FENGSHA in CMAQ

A new windblown dust emission module (FENGSHA) was developed for CMAQv4.7. The FENGSHA model considers four land types as potential erodible dust sources (barren land, shrub-grass land, shrub land and agricultural land: see Fig. 2b). The vertical flux F (g m^{-2} s^{-1}) is calculated based on a modified Owen saltation formula (Owen, 1964; Gillette and Passi, 1988),