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Spatial and temporal variations of spring dust emissions in northern China over the last 30 years

Hongquan Song [a], Kesheng Zhang [a], Shilong Piao [b], Shiqiang Wan [a, *]

[a] College of Life Sciences, State Key Laboratory of Cotton Biology, Key Laboratory of Plant Stress Biology, Henan University, Kaifeng, Henan 475004, China
[b] Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

HIGHLIGHTS

- Spatial pattern of dust flux in northern China over last 30 years was simulated.
- Temporal trend of dust emissions in northern China over last 30 years was simulated.
- Climate change and human activities significantly influence dust emissions in China.

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ABSTRACT

Dust emissions caused by wind erosion have significant impacts on land degradation, air quality, and climate change. Dust from the arid and semiarid regions of China is a main contributor to atmospheric dust aerosols in East Asia, and their impacts can stretch far beyond the territory of China. Spatial-temporal patterns of dust emissions in China over the last several decades, however, are still lacking, especially during the spring season. In this study, we simulated the spatial-temporal dynamics of spring dust emissions from 1982 to 2011 in arid and semi-arid areas of China using the Integrated Wind Erosion Modeling System. Results showed that the most severe dust emission events occurred in the Taklimakan Desert, Badain Jaran Desert, Tengger Desert, and Ulan Buh Desert. Over the last three decades, the magnitude of spring dust emissions generally decreased at the regional scale, with an annual spring dust emission of ~401.10 Tg. Among different vegetation types, the highest annual spring dust emission occurred in the desert steppes (~163.95 Tg), followed by the deserts (~103.26 Tg). The dust emission intensity in the desert steppes and the deserts was ~150.83 kg $km^{-2} \cdot yr^{-1}$ and ~205.46 kg $km^{-2} \cdot yr^{-1}$, respectively. The spatial patterns of the inter-decadal variation are related to climate change and human activities. Mitigation strategies such as returning farmland to grassland, fenced grazing, and adequate grass harvesting, must be taken to prevent further soil losses and grassland degradation in northern China.

1. Introduction

Wind erosion is a natural geological process that includes detachment, transport, and deposition of soil particles by strong winds (Li et al., 2007; Hoffmann et al., 2011). It is a major soil degradation process in arid and semi-arid areas of the world (Gregory et al., 2004; Buschiazzo and Zobeck, 2008; Webb et al., 2009). Global dust emissions are estimated to range from 1018 Tg yr^{-1} (Miller et al., 2004) to 3000 Tg yr^{-1} (Tegen and Fung, 1994), which accounts for approximately 30%–50% of the total aerosol injections into the atmosphere (Alfaro, 2008). Dust aerosols have significant impacts on the Earth's radiation budget, global biogeochemical cycles, terrestrial soil formation, atmospheric chemistry, air quality, and public health (Chadwick et al., 1999; Reynolds et al., 2001; Jickells et al., 2005; Li et al., 2007; Alfaro, 2008; Chappell et al., 2012). In addition, the detachment and transport of dust can significantly lower soil fertility and water holding capacity in dust source areas (Li et al., 2007). The deposition of dust may also have significant beneficial effects, however, such as the transport of organic carbon (Chappell et al., 2012, 2013), nitrogen (Mace et al., 2003), phosphate (Eger et al., 2013), iron

* Corresponding author. College of Life Sciences, Henan University Jinming Campus, Kaifeng, Henan Province, China.
E-mail address: swan@henu.edu.cn (S. Wan).

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(Conway et al., 2015; Horner et al., 2015), and other essential nutrients from the soil to terrestrial and aquatic ecosystems that can enhance primary productivity (Chadwick et al., 1999; Neff et al., 2008; Field et al., 2009).

In order to assess the impacts of dust emissions on socio-economics and the environment, it is essential to quantify the wind erosion rates at different spatial and temporal scales. Wind erosion is affected by complex interactions among soil properties, climate, vegetation, and land management (Lu and Shao, 2001; Hoffmann et al., 2011; Aubault et al., 2015). Several approaches have been taken to measure the physical properties and driving factors of wind erosion. For example, mathematical simulations are used to derive the relationships between meteorological records and interacting surface parameters (McTainsh et al., 1998). Remote sensing and geographic information systems (GIS) are applied to estimate the wind erosion intensity (Zobeck et al., 2000; Maman et al., 2011; Guo et al., 2013), while further identifying dust sources (Ginoux et al., 2004). A large number of wind erosion models have been developed to quantify wind erosion rates, soil losses, and dust emissions at the local (Fryrear et al., 1998, 2001; Okin, 2008), regional (Lu and Shao, 2001), and global scales (Webb et al., 2009).

In northern China, wind erosion is a serious environmental problem, especially in arid and semi-arid regions (Chen et al., 2014) that experience heavy and long-term grazing. The average annual soil dust emission in East Asia is ~214 Tg (Tanaka and Chiba, 2006), and 32% of these emissions occur in northern China (Tanaka and Chiba, 2006). To identify dust sources and sinks in China, a wind erosion risk map with high spatial resolution has been developed based on remote sensing images (Reiche et al., 2012). With the integration of remote sensing, experiments, and field observations, Liu and Wang (2014) have explored aeolian processes and landscape changes of the Sonid grassland in northern China. Using meteorological (Sun et al., 2001) and remote sensing data (Taramelli et al., 2012; Gong et al., 2014), spatial-temporal variations of dust storms and wind erosion intensity have been examined over the last several decades in northern China.

Few studies have investigated spatial and temporal variations of dust storms or land desertification (Sun et al., 2001; Wang et al., 2004), however, spatial patterns and temporal trends of the quantity of soil losses due to wind erosion over the last several decades in northern China remain limited. To improve on this limitation, in this study, we simulate the spatial-temporal variations of spring dust emissions during the period 1982–2011, using the Integrated Wind erosion Modeling System (IWEMS; Lu and Shao, 2001). Moreover, direct links between regional climate change and dust emissions have not yet been made. Thus our study will also attempt to discuss the interconnections that exist between dust emissions and climate change in northern China over the last three decades.

2. Materials and methods

2.1. Study area

This study area is located in hyper arid, arid, and semiarid regions in northern China (Fig. 1), which accounts for 30% of the total area of China, and is classified as a temperate continental climate, including vegetation types such as grasslands, shrublands, and deserts. The mean annual precipitation is generally less than 400 mm in research region.

2.2. Wind erosion model description

IWEMS is a process-based model developed by Lu and Shao (2001), and consists of an atmospheric model, a land surface scheme, a wind erosion scheme (for dust emission and sediment drift), a dust transport and deposition scheme, and a geographic information database (Shao et al., 2002). The atmospheric model provides relevant data (e.g. wind velocity and eddy diffusivity) used in driving both the wind erosion and dust transport model. In order to compute the dust emission rate, relevant atmospheric data and land surface data are passed to the wind erosion scheme at each physical time step. The GIS database provides the spatially distributed land surface data (e.g. soil properties, friction velocity) required for the wind erosion scheme. The dust emission data produced by the dust emission model are then passed to the dust transport model together with atmospheric data for the prediction of dust motion (Shao et al., 2003). The IWEMS has been extensively used to simulate dust over East Asia (Shao et al., 2002; Mao et al., 2011, 2013; Du et al., 2014).

2.3. Datasets

The land surface variables required by the IWEMS are soil properties, vegetation cover, and land use. Soil variables (e.g., soil types, soil bulk density) are obtained from the Harmonized World Soil Database (HWSD) with a map scale of 1:1,000,000. Land use maps with a map scale of 1:100,000 in 1980s, 1995, and 2000 are obtained from the Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn/), which are integrated with soil data to extract the fraction of erodible area according to the methods in Lu and Shao (2001). The monthly vegetation cover is calculated from the normalized deviation vegetation index (NDVI) formula of Gutman and Ignatov (1998). The NDVI datasets for 1982–2011 are obtained from the Global Land Cover Facility, Global Inventory Modeling and Mapping Studies (Tucker et al., 2005), which have a spatial resolution of 8 km $\times$ 8 km. Wind field datasets are provided by the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis datasets, which are updated every six hours with a spatial resolution of $2.5^\circ \times 2.5^\circ$. To drive the IWEMS, these three datasets are projected to the same spatial coordinate system using the Albers map projection, and are also re-gridded to the same spatial resolution of 8 km $\times$ 8 km.

To validate the performance of the IWEMS, simulation output is compared to the daily spring dust storm frequency data observed at 283 meteorological stations during the period 1982–2007, which are obtained from the meteorological network of the China Meteorological Administration (Zhou et al., 2006). Dust comparison data are further used to explore the relationship between the dust storm frequency and the dust emissions. Daily wind velocity, precipitation, and temperature at 365 meteorological stations over the last 30 years in the research region are obtained from the China Meteorological Data Center (http://data.cma.gov.cn). Meteorological comparison data are further used to explore the impacts of inter-decadal change of wind velocity, precipitation, and temperature on dust emissions in northern China over the last three decades.

2.4. Model simulation and validation

This study uses the IWEMS to simulate the spatial patterns of dust flux and the quantity of dust emissions at a regional scale in the spring season of March 1 to May 31 during the period of 1982–2011. IWEMS is driven by atmospheric conditions that are updated every 6 h, vegetation cover that is updated annually, and land surface properties that are either updated on a decadal scale (e.g., land use), or held constant (e.g., soil properties) depending on the land surface variable. Soil moisture is not included because the arid and semi-arid areas studied in this work experience minimal