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Responses of aeolian desertification to a range of climate scenarios in China

Xunming Wang[1, 2], Ting Hua[1, 2], Wenyong Ma[1]

[1] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2] Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

Correspondence to: Xunming Wang (xunming@igsnrr.ac.cn)

Abstract. Aeolian desertification plays an important role in earth-system processes and ecosystems, and has the potential to greatly impact on global food production. The occurrence of aeolian desertification has traditionally been attributed to increases in wind velocity and temperature, and decreases in precipitation. In this study, by integrating the aeolian desertification monitoring data and climate and vegetation indices, we found that although aeolian desertification is influenced by complex climate patterns and human activities, increases in precipitation and temperature, and decreases in wind speed, may also trigger aeolian desertification in China. Our results show that, even when modern technical approaches are used, different approaches to desertification need to be applied to account for regional differences. These results have important implications for future policy decisions on how best to combat desertification.

1 Instruction

In China, aeolian desertification mainly occurs when anchored or semi-anchored dunes are reactivated (Zhang et al., 2014; Wang et al., 2015), and when arable land and grassland are degraded to such a degree that aeolian transport is exacerbated by decreases in vegetation cover or increases in the intensity of aeolian processes (Wang et al., 2005; Houyou et al., 2014;

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Martínez-Graña et al., 2015). Over the past five decades, there have been several periods with high or low rates of dune reactivation and degradation of arable land and grassland, with corresponding occurrences of desertification and rehabilitation. Aeolian desertification may give rise to land surfaces that can no longer support cultivation or husbandry (UNCD, 1977; United Nations, 1992), and cause decreases in biomass and species richness, loss of herbaceous species, and reductions in crop and meat production (Schlesinger et al., 1990; Reynolds et al., 2001; Wang et al., 2008; Okin et al., 2009). Land that is at risk from aeolian desertification in China is mainly located on the boundaries of sandy and gobi deserts. The affected area stretches from central Asia in the west to northeastern China in the east, and covers more than 1.83 million km^2 (DCSNBSC, 2005; State of Forestry Administration of China, 2011) and occupies almost 70% of the total area at risk from desertification. This land is currently managed as traditional pastoral and agricultural systems, but if aeolian desertification continues to expand the livelihoods of nearly 400 million people will be jeopardized (DPSSTS, 2002). By the mid-2000s, costs associated with the loss of loess attributable to aeolian desertification exceeded 50 billion RMB (approximately 8 billion USD) (Central People's Government of the People's Republic of China, 2005).

Increases in wind speed and decreases in precipitation have traditionally been considered to increase aeolian processes, erode fine particles and nutrients from soil surfaces (Xu and Zhang, 2014; Xie et al., 2015), and trigger aeolian desertification (Okin and Gillette, 2001; Field et al., 2009; Sankey et al., 2012). Aeolian processes may also impact on ecosystems (Vieira et al., 2015), as windblown dust inputs can contribute to soil formation and provide essential nutrients (Reynolds et al., 2007), indirectly moderate plant communities in the receiving area (Munson et al., 2011), promote land rehabilitation, and introduce plants to areas far from their natural habitat. In addition,

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although there is uncertainty regarding the contribution of variations in temperature to global terrestrial net primary production (Balling, 1991; Nemani et al., 2003), it has been predicted that global warming in the early 21st century may promote rehabilitation of most of the regions of China currently at risk from desertification (Wang et al., 2009; Miao et al., 2015).

Given the huge potential risks to ecological security, pastoral and agricultural systems, and crop and meat production posed by aeolian desertification, national and district level governments in China implemented numerous programs between the 1970s and early 2010s (Zhu, 1994; Ministry of Science and Technology of the People's Republic of China, 2005) to extensively monitor, mitigate, and control aeolian desertification throughout China. Even though the effectiveness of some desertification control programs has been questionable (Wang et al., 2010), and the impacts of human activity on desertification have been overestimated (Wang et al., 2006), to date, no consideration has been given to variations in the predominant climatic factors and their impact on desertification. Without robust testing, the most common mitigation measures applied throughout China have been afforestation, conversion of tilled land to forestry and grassland, and prevention of grazing (The State Council of People's Republic of China, 2002; 2007).

Even with modern technological tools, the principle methods used to mitigate aeolian desertification in China still rely on improved moisture conditions and decreases in wind velocity (The Central People's Government of the People's Republic of China, 2013). However, regional differences mean that, in some regions, the process of desertification is highly sensitive to variations in precipitation, whereas in other regions it is highly sensitive to variations in wind velocity and temperature (Wang et al., 2008). In this study, we integrated variations in trends in temperature, wind velocity, and precipitation, and determined their relationships with aeolian

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desertification in China.

2 Materials and methods

2.1 Materials

2.1.1 Aeolian desertification monitoring programs

There have been five Aeolian desertification monitoring campaigns over the past 40 years. Based on these monitoring results, and using the monitoring criteria listed in Table S1, aeolian desertification has been categorized into four aeolian desertification, namely: slight, moderate, severe, and very severe. Subsequently, the entire area of China at risk from aeolian desertification was divided into 29 areas (4 overlapping regions were excluded from the main part of this contribution and the results have been included in the supplementary material) using the monitoring criteria (Figure S2). Monitoring was carried out in 1975, 1990, 2000, 2005, and 2010, and detailed results have been reported by (Wang, 2014). These monitoring programs mainly involved remote sensing and field investigations, and statistical analysis showed that in regions with a high risk of aeolian desertification, there were no close relationships between vegetation conditions and the results of aeolian desertification (Figure S2).

2.1.2 NDVI data

The Normalized Difference Vegetation Index (NDVI) dataset for the period 1982–2010 was acquired from the third generation Global Inventory Modeling and Mapping Studies (GIMMS) NDVI dataset (Pinzon and Tucker, 2014). This dataset has a spatial resolution of $1/12° \times 1/12°$ and a temporal resolution of 15 days. The highest NDVI value from each 15-day period was extracted and combined into the annual NDVI data using the maximum value compositing (MVC) technique (Holben, 1986).

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2.1.3 Vegetation cover data

The NDVI method for the dimidiate pixel model was used to acquire the vegetation fractional cover data (VFC) (Wittich and Hansing, 1995; Xiao and Moddy, 2005), which is expressed as follows:

$$VFC = (NDVI - NDVI_{soil})/(NDVI_{veg} - NDVI_{soil}) \quad (1)$$

where $NDVI_{soil}$ is the NDVI value of a bare surface or of an area with no vegetation cover, and $NDVI_{veg}$ is the NDVI value of an area with full vegetation cover.

2.1.4 Temperature, precipitation, and wind velocity data

Temperature, precipitation, and wind velocity data from 750 meteorological stations around China were acquired from the Chinese Meteorological Administration. Mean annual data were spatially interpolated using the inverse-distance-weight (IDW) method.

2.1.5 PDSI data

Monthly values of the Palmer Drought Severity Index (PDSI) with a temporal resolution of 2.5° × 2.5° were used to evaluate variations in atmospheric moisture supply and demand (Palmer, 1965). This index incorporated the antecedent and current moisture supply and demand into a hydrological model that includes a two-layer bucket type model for soil moisture calculations (Dai et al., 2004).

2.2 Methods

In order to estimate the relationship between aeolian desertification and climate factors, Spearman correlation coefficients were calculated between areas of aeolian desertification and the climate indices in the overlapping monitoring regions. Before the Spearman correlations were performed, all climate and vegetation indices were divided into periods that corresponded with the monitoring

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intervals for aeolian desertification (Table S2). In addition, the NDVI and VFC data only became available after 1982; therefore, the averaged data from 1982 to 1990 were analyzed with the monitoring results of aeolian desertification from 1990.

3 Results and discussion

Our results show that, for most regions with high risks of aeolian desertification, variations in precipitation and the occurrence of aeolian desertification are not closely related (Figure 1a), and increases in precipitation have only beneficial to the rehabilitation that has taken place in areas such as the Tarim Basin, the source area of the Yellow River, the Qinghai Lake Basin, and the Heihe and Kashgar Drainage areas. In contrast, in areas such as the Junggar Basin, the Turpan-Kumul Basin, the Kashgar Drainage Basin, and the northeastern autonomous region of Ningxia, increases in precipitation gave rise to slight to moderate aeolian desertification.

Figure 1

As with the response of aeolian desertification to variations in precipitation, the responses of aeolian desertification to various degrees of temperature increase were variable (Figure 1b). In China, increases in temperature are beneficial for rehabilitation in areas where there is a high risk of aeolian desertification, such as the Tarim Basin, the Kashgar Drainage area, the Qaidam Basin, Qinghai Lake Basin, the Tangier Desert, and the lower reaches of the Yellow River that have been classified with different desertification grades. Further, our results show that, for most regions, there are no close relationships between variations in wind velocity and aeolian desertification (Figure 1c), and increases in wind velocity resulted in aeolian desertification only in areas such as the Qinghai Lake Basin, and the Badain Jaran and Tengger deserts. In particular, our statistical results show that increases in wind speed may promote rehabilitation in areas with changeable

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aeolian desertification grades, such as the Junggar Basin, the Turpan-Kumul Basin, the Qaidam Basin, the Zoige Plateau, the Mu Us Desert, and the Xilin Gol Grasslands.

Similar to the relationships between aeolian desertification and variations in precipitation, temperature, and wind velocity, there are also spatial variations in the responses of aeolian desertification to surface soil moisture conditions (Figure 1d). For example, correlation analysis between the Palmer Drought Severity Index (PDSI) and areas impacted by aeolian desertification shows that increases in soil moisture may result in rehabilitation in the Junggar Basin, the Kachgar Drainage area, the Qaidam Basin, the Luanhe-Yongding drainage area, and Qinghai Lake basin regions, but may trigger slight aeolian desertification in the Turpan-Kumul Basin and the lower reaches of the Yellow River, which is not consistent with the conventional perception that increases in the PDSI may improve rehabilitation of the region (Jeong et al., 2011; Peters et al., 2012). In addition, our results show that, just as there is variation between the monitoring areas, the correlations between the areas impacted by aeolian desertification and climate indices are also variable. Within limited areas, the degree of aeolian desertification is highly sensitive to the intensity of the aeolian processes (Wang et al., 2008), which results in variable relationships between the responses of aeolian desertification and climate indices. These results also suggest that regionalization is a vital issue for desertification mitigation programs. Furthermore, although the impacts of climate change on land degradation are only visible after a relatively long period (Herrmann et al., 2005; Vicente-Serrano et al., 2013), monitoring results that extend beyond periods of five years indicate that, in addition to the lagged responses of aeolian desertification to various climate indices, increases in precipitation and temperature, and decreases in wind velocity, may also trigger aeolian desertification at the regional scale, and may therefore introduce uncertainty

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into assessments of the impacts of climate change on landscape evolution.

Over the past five decades, human activities such as reclamation and increased grazing intensity in China may have accelerated the process of aeolian desertification (Wang et al., 2006); however, other human activities that can be beneficial to rehabilitation, such as afforestation, conversion of tilled land to forestry and grassland, and prevention of grazing, have also been put into practice (Cao et al., 2011). To some degree, the inconsistency of these practices has also contributed to the confusing response of aeolian desertification to various climate indices. Nevertheless, regions with high risks of aeolian desertification in China are mainly concentrated in arid, semiarid, and semi-humid areas, within which the intensity of human activity is very low (SI Text S1). Therefore, despite the undeniable impact of human activities in China, the role of climate change on desertification and rehabilitation may be more important (Wang et al., 2006).

4 Conclusions

Although increases in precipitation and surface soil moisture conditions, and decreases in wind velocity may be promote rehabilitation over longer timescales and across larger spatial scales, they also may trigger aeolian desertification in some areas. Monitoring of aeolian desertification in China over recent decades shows that desertification has responded in various ways to climate indices. Even when modern technical approaches are applied, the complex patterns of climate and human activities, and the variability between regions, mean that a range of desertification control practices should be applied. This information has important implications for future policy decisions on how best to combat desertification.

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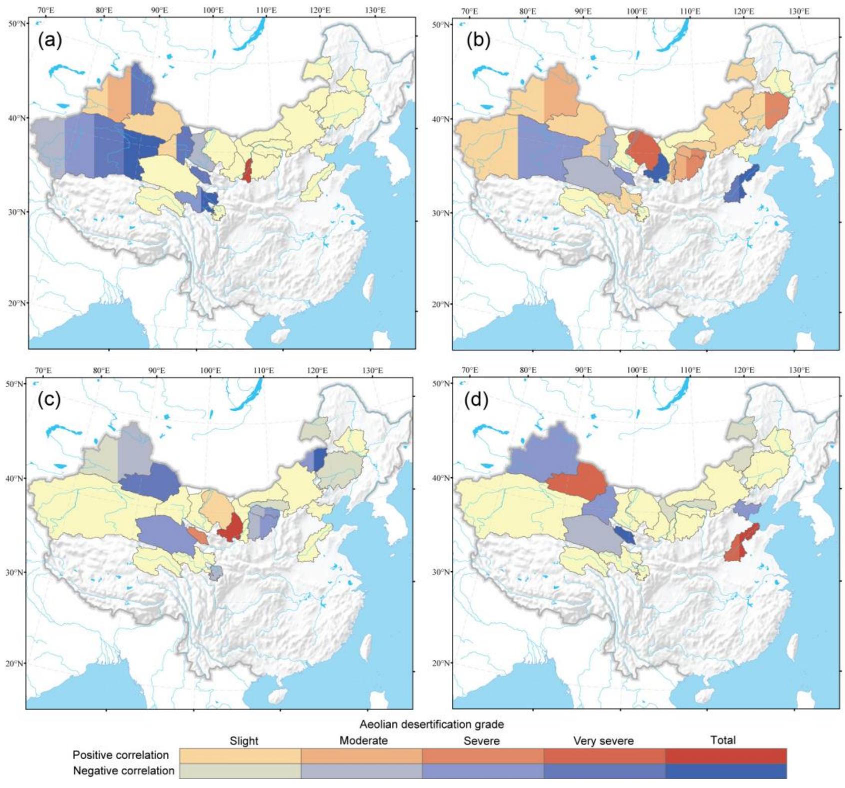

Figure 1. Spearman correlations between variations in areas of aeolian desertification and (a) precipitation, (b) temperature, (c) wind velocity, and (d) the Palmer Drought Severity Index (PDSI). Main areas where aeolian desertification monitoring takes place are shown in Figure S2. Regions where negative/positive correlations are significant at the 0.05 level (2-tailed) are shown in blue/red colors, and regions where correlations were not significant at the 0.05 level (2-tailed) are shown in yellow. Detailed correlation results are provided in the supplementary texts and tables.