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The Influence of Vegetation Variation on Northeast Asian Dust Activity

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Abstract: In this study, we investigate the influence of vegetation variations on dust activity (dust load, dust transport in the troposphere, and dust weather frequency) over Northeast Asia during springtime. By using the Integrated Wind Erosion Modeling System, two model experiments are run over four-month periods, from February 1 to May 31, for each year from 1982 to 2006; one experiment uses the observed atmospheric conditions and vegetation (OBS), and the other uses the specified atmospheric conditions in 2006 and the observed vegetation (CTRL). Comparison of the two model experiments reveals that there are sensitive regions in southeastern Mongolia and central northern China, in which vegetation has a large potential to influence dust activity due to both the high dust emission rate and large variations in vegetation coverage. Over these sensitive regions, vegetation effectively lessens dust loads on interannual and interdecadal timescales; dust load is decreased by 2864 $\mu g\ m^{-2}$ for an increment of 0.1 in the normalized difference vegetation index (NDVI). Vegetation increase in the sensitive areas also reduces two major branches of dust transports in the low troposphere; one stretches from eastern Mongolia to regions northeastward, and the other flows across the south of northeastern China to Korea. In addition to dust loads and transports, vegetation increase in the sensitive areas evidently decreases dust storm frequency and blowing dust frequency, but it exerts a weak influence on the floating dust frequency. In the sensitive regions, as NDVI increases by 0.1, dust storms, blowing dust, and floating dust decrease by 4.0 days/spring, 1.5 days/spring, and 0.2 days/spring, respectively. In summary, vegetation variations in southeastern Mongolia and central northern China have considerable impact on northeast Asian dust during springtime.

Key words: Vegetation, Northeast Asian dust, Integrated Wind Erosion Modeling System

1. Introduction

Vegetation is considered to be one of the main factors affecting dust emission and dust storm occurrence (Tegen *et al*., 2002; Engelstaedter *et al*., 2003; Shinoda *et al*., 2011). Higher vegetation cover results in higher surface roughness length and less dust emission, thereby reducing dust storm occurrence. Many observational and modeling studies have examined the impact of vegetation on dust activity in northeast Asia. It is noted that dust storms frequently occur in northeast Asia during spring (Natsagdorj *et al*., 2003; Zhou *et al*., 2003). Depending on desert reversal scenarios within natural precipitation zones in dust modeling, Gong *et al*. (2003) indicated that the restoration of vegetation cover in the 200-400 mm annual precipitation zone of Chinese deserts decreased the surface mass concentrations by 10-50%. Zou *et al*. (2004) identified a negative correlation between vegetation coverage and dust storm occurrence in northern China for the springs of 1982-2001. Lee and Sohn (2009) found that in the Taklimakan and Gobi Deserts, dust weather occurrences largely depend on wind speed rather than vegetation, but in eastern Inner Mongolia, the increase in vegetation may prevent dust outbreaks even under the occurrence of strong winds.

While many studies have analyzed the influence of vegetation on northeast Asian dust activity, there are two large uncertainties involved with vegetation variations: (1) the meteorological conditions, which influence the vegetation-dust relationship, and (2) the contribution of vegetation changes to the variations in dust weather and dust transport in the low troposphere. It is noted that vegetation influences dust occurrence in conjunction with meteorological conditions (e.g., surface wind), and together they bring about dust outbreaks synergistically. However, under different meteorological conditions, the influence of vegetation on dust activity also would vary. For instance, in some circumstances, severe weather may weaken the influence of vegetation on dust activity, but this vegetation impact becomes strong under mild weather. To measure the pure influence of vegetation on dust activity, the meteorological conditions should be specified, and then the variations of dust activity under different vegetation changes need to be examined. Some modeling studies have used the same meteorological conditions to measure the influence of vegetation changes upon surface dust concentration (e.g., Gong *et al*., 2003). However, as these studies could not account for the influence of vegetation on dust weather and the variations of surface dust concentration cannot accurately reflect the changes in dust weather frequency (Zhao *et al*., 2006), it is natural to examine the extent to which vegetation change contributes to the variability of dust weather.

Nevertheless, dust aerosols produced by dust storms would

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have an influence on climate change. Dust aerosols directly modify the radiative balance by changing the reflection, scattering, and absorption of solar radiation (Tegen *et al*., 1996), and indirectly affect climate variations by their interaction with clouds and marine biological activities (Chadwick *et al*., 1999). The spatial and vertical distributions and amount of dust aerosols in the troposphere are determined by dust transport. However, few studies have addressed the effect of vegetation on dust transport in the troposphere (Sugimoto *et al*., 2010). Data regarding dust transport, beginning from the dust source location, are unfortunately scarce, and this lack of empirical data is the primary reason for the dearth of modeling investigations. Nevertheless, dust modeling data are sufficient to allow research to be conducted.

In this study, by using an Integrated Wind Erosion Modeling System (IWEMS), we will identify sensitive regions where vegetation can significantly influence dust activity, and then measure the contribution of vegetation changes over the regions that are important to dust emission, dust weather, and dust transport over northeast Asia for the period from 1982 to 2006.

2. Model and data

a. Model description

The IWEMS has been widely employed in dust simulations in East Asia. The IWEMS can reasonably reproduce the dust process in northeast Asia, including dust emission, dust concentration, and other dust variables (Shao *et al*., 2003). Mao *et al*. (2011a, b) has implemented this model to study northeastern Asian dust for the period from 1982 to 2006, and has analyzed the effects of the Arctic Oscillation on dust activity over East Asia. The IWEMS consists of modeling, monitoring, database, and data assimilation components. The modeling component comprises an atmospheric model and modules for land-surface processes and dust emission, transport, and deposition. The atmospheric model-either global, regional, or meso-scale-serves as a host for other modules. The atmospheric models consist of advanced numeric models of atmospheric dynamics and physical processes such as radiation, clouds, convection, and turbulent diffusion. A land-surface scheme simulates the energy, momentum, and mass exchanges among the atmosphere, soil, and vegetation. For dust modeling, the land-surface scheme produces friction velocity and soil moisture as outputs. Considering three major dust emission mechanisms (aerodynamic entrainment, saltation bombardment, and aggregates disintegration), the dust emission scheme obtains friction velocity and soil moisture from the land-surface scheme and other spatially distributed parameters from the geographical information system (GIS) database, and calculates the dust-emission rates for different particle size groups. To predict dust motion, the transport and deposition model obtains wind, turbulence, and

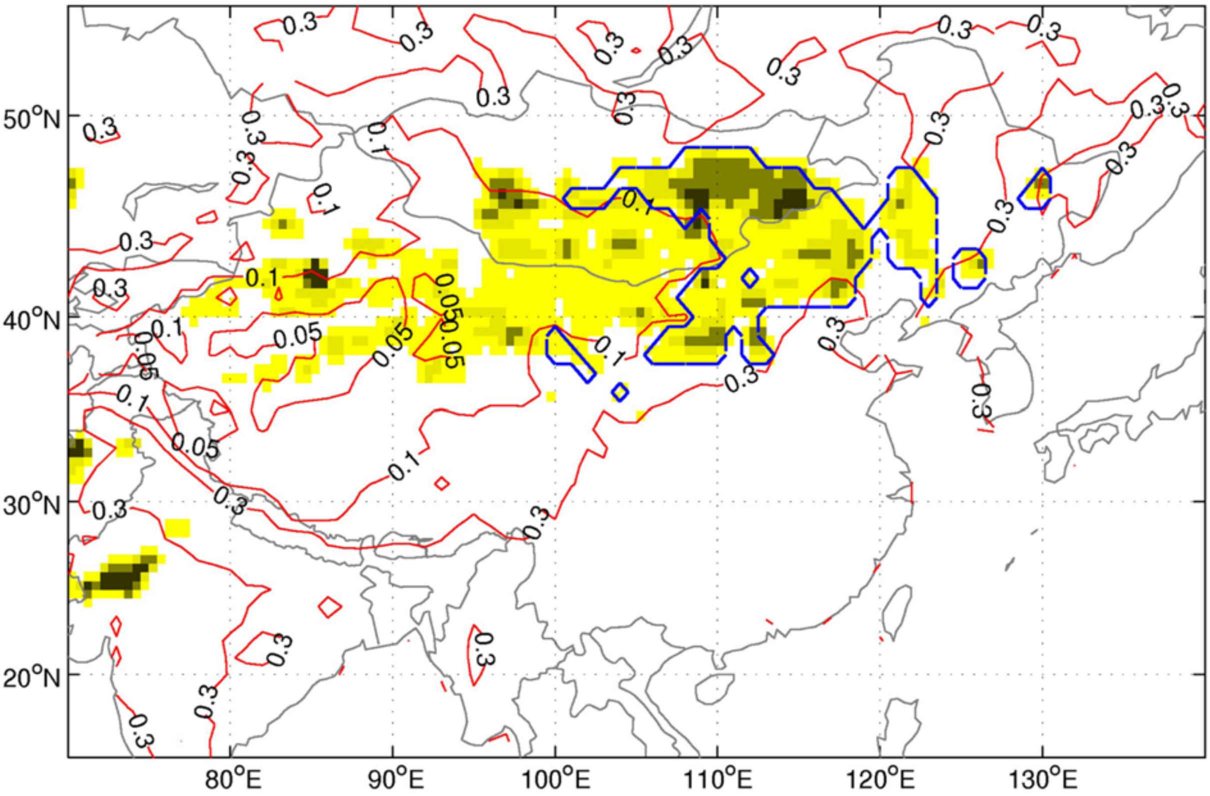

Fig. 1. The climatology of dust emission rate (unit: $\mu g\ m^{-2} s^{-1}$) and the NDVI in northeast Asia in spring. The light and heavy shadings indicate climatological dust emission rates exceeding 10 and 50, respectively. The contour lines represent the climatological NDVI. The regions enclosed by blue dashed lines are the sensitive regions in this study.

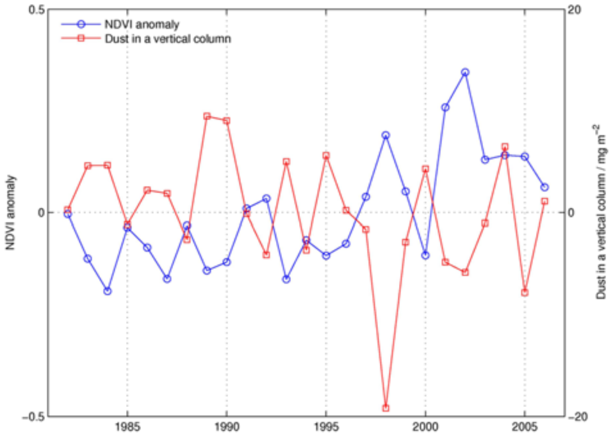

Fig. 2. The anomaly of the spring dust load (unit: mg m^{-2}) and the spring NDVI in the sensitive regions retrieved from the CTRL experiment.

precipitation data from the atmospheric model and dust emission rate and particle-size information from the dust-emission model (Shao *et al*., 2004).

We have verified the modeling ability of IWEMS by comparing the spatial distributions of dust storm frequency (DSF) derived from observations and simulations, and by comparing the observations and simulation results for the time series of domain-averaged DSF over North China (see Figs. 2 and 3 in Mao *et al*., 2011a). In general, the model reasonably reproduces the observed spatial distribution of dust activity. The spatial features of the simulated DSF are consistent with the observations, in which the maximum DSF occurs in regions such as the Taklimakan Desert and arid areas in northern China and a relatively low DSF occurs in northeastern China. In addition, the simulated time series of DSF over northeast China shows good agreement with that from the observations; these two time series have a correlation coefficient of 0.70 (significant at the 95% confidence level). Based on the comparison between observations and simulations, we are confident that this model is able to simulate the annual evolution of spring dust episodes and that is able to accurately capture the major interannual variations in dust characteristics shown in the observations.

b. Data

The vegetation data needed for the IWEMS are vegetation cover (VC) and leaf area index (LAI). In this study, the VC is obtained from the normalized difference vegetation index (NDVI) by means of an algorithm developed by Gutman and Ignatov (1998). The NDVI values for the period from 1982 to 2006 are obtained from the Global Land Cover Facility, Global Inventory Modeling and Mapping Studies (Tucker *et al*., 2005). The LAI data is from the climate and vegetation research group at Boston University (Ganguly *et al.*, 2008). The atmospheric conditions used for the IWEMS are taken from the National Center for Environmental Prediction and National Center for

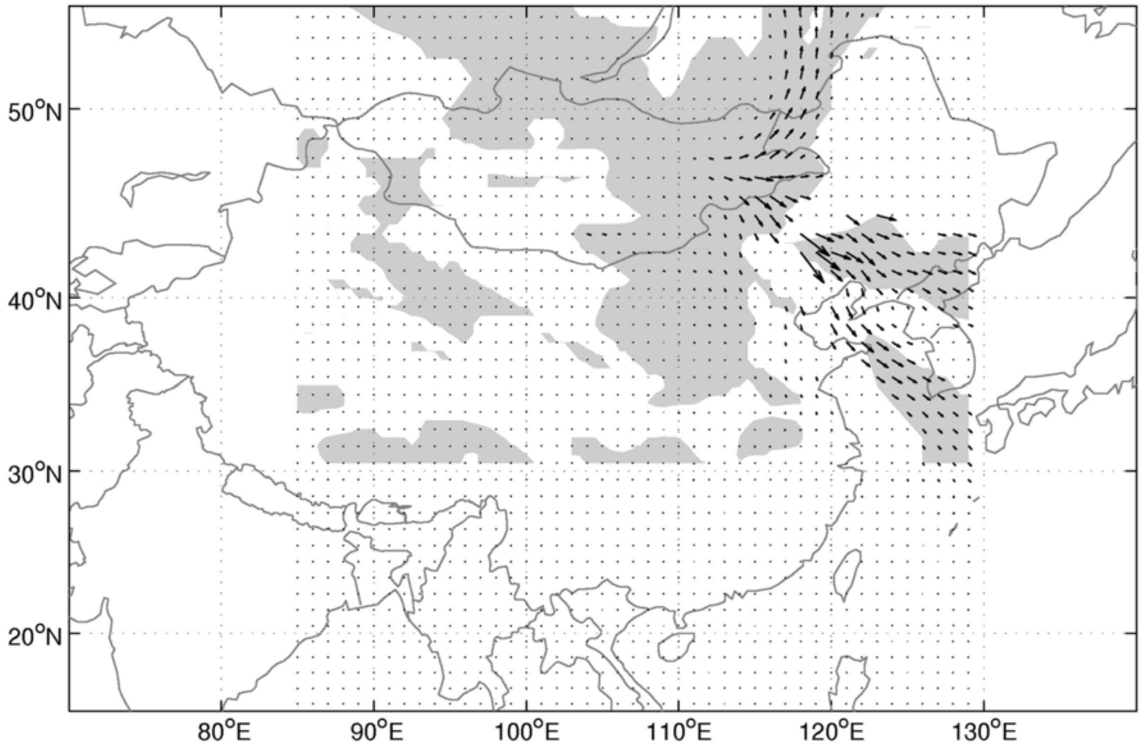

Fig. 3. The dust transport flux variations in the lower troposphere (average of dust transport flux at 0.90-0.78 sigma levels) induced by vegetation changes in the sensitive regions. The shadings indicate the dust transport flux variations that are significant at the 95% confidence level. For clarity, the dust transport flux (unit: μg m^{-2} s^{-1}) is expressed as a vector; its direction is reversed and indicates the decreased dust transport direction. The largest vector length represents a magnitude of 190 μg m^{-2} s^{-1}.

Atmospheric Research (NCEP-NCAR) reanalysis data with a spatial resolution of 2.5° for both longitude and latitude. The meteorological variables used include wind, temperature, geopotential height, and sea level pressure. During the whole simulation period, atmospheric conditions were updated every 6 hours, while the vegetation was updated monthly. During the simulation, atmospheric conditions were interpolated to a finer horizontal resolution (50 km) via linear interpolation, which is consistent with that of the vegetation data.

c. Methodology

Two model experiments were conducted in this study: one using observed atmospheric and vegetation conditions (OBS) for the modeling period, and the other using the specified atmospheric conditions and observed vegetation (CTRL). A range of parameters such as vegetation height, VC, LAI, minimum vegetation stomatal resistance, vegetation albedo, and root distribution were equally imbedded into both experiments. The OBS was run over four-month periods from February 1 to May 31, for each year from 1982 to 2006, for which the real-time dust weather was simulated, and the variations in dust activity were caused by the collective effect of the observed atmospheric and vegetation conditions. The CTRL was also run over the same four-month periods from February 1 to May 31, from 1982 to 2006, but the atmospheric conditions in each year were taken from the conditions in 2006. Hence, the CTRL simulations show the influence of the vegetation changes on the northeast Asian dust activity under the atmospheric conditions in 2006. The reason that the atmospheric conditions in 2006 were employed in the CTRL experiment is that this year was the most neutral year for the atmospheric conditions from 1982 to 2006.

In this study, dust activities in the spring were analyzed, and the simulations for spring (March, April, and May) were analyzed as springtime dust activities. In addition, for simplicity, the NDVI was analyzed, rather than the LAI and VC, in order to reveal the impact of vegetation changes on dust activity because the NDVI in the semi-arid and arid areas was linearly related to the VC and LAI (Carlson and Ripley, 1997).

3. Climatological features of dust emission and vegetation

Vegetation is closely related to dust activity via its influence on dust emission in wind erosion processes. Dust emissions are minor in densely vegetated surfaces and are subject to high amounts in most semiarid and arid areas covered with little vegetation. Thus, the spatial distributions of the coupling of vegetation and dust emission determine the sensitive regions where vegetation has a large influence on the dust activity. To identify these sensitive regions, a climatological distribution of dust emission and vegetation in northeast Asia during the years 1982-2006 are displayed in Fig. 1. The climatology of spring vegetation and the dust emission rate was obtained from the OBS simulations. As seen in the figure, a high dust emission rate ($\geq 10\ \mu g\ m^{-2}\ s^{-1}$) appeared in the majority of northern China and southern Mongolia, with the highest rate ($\geq 100\ \mu g\ m^{-2}\ s^{-1}$) mainly located in southeastern Mongolia and central northern China. Figure 1 also shows the climatological NDVI in the spring; the NDVI varied from 0.05 in northwestern China to 0.3 in southeastern China. It is less than 0.05 in the Taklimakan Desert, between 0.05 and 0.1 in the west of northern China and southern Mongolia, 0.1-0.3 in the central and eastern parts of northern China and southeastern Mongolia, and larger than 0.3 in eastern China.

According to the climatological distributions of the NDVI and dust emission, it is found that the impact of vegetation on dust emission varied from region to region. This regional difference is due to variations in the vegetation-dust-emission coupling. Regions where vegetation has a large potential to influence dust emission may have large variations in the NDVI and a high dust emission rate; in contrast, a minor influence of vegetation on dust emission may occur in the areas with minor variations in the NDVI and/or a low dust emission rate. Based on this hypothesis, the following criteria are used to identify sensitive areas, in which vegetation has a large influence on dust activity: (1) the climatological NDVI in the spring is ≥ 0.1, and (2) the climatological dust emission rate is $\geq 10\ \mu g\ m^{-2}\ s^{-1}$. Using these criteria, the sensitive areas are outlined. These sensitive regions are in southeastern Mongolia and central northern China (enclosed by dashed lines in Fig. 1, located in the ranges 105°E-125°E and 38°N-48°N). By taking the spatial average, the dust emission rate in these regions was found to be $\geq 40\ \mu g\ m^{-2}\ s^{-1}$, and the NDVI was between 0.1 and 0.3. These sensitive regions, though smaller, were consistent with the sensitive regions reported by observational analysis (Lee and Sohn, 2009). Lee and Sohn (2009) analyzed the climatological distributions of dust occurrence, wind speed, and NDVI in northeast Asia. They argued that eastern Mongolia, central northern China, and parts of northeast China were important regions for vegetation impact on dust activity.

While not shown in the figure, we have examined the long-term trend of the NDVI during the years 1982-2006 over northeast Asia. It is found that during springtime, the NDVI over these sensitive areas showed an evident increasing trend. The average rate of increase of the NDVI was 0.008 decade^{-1} (significant at the 99% confidence level); in contrast, there is no evident seasonal or long-term variation in the NDVI over the west of northern China or western Mongolia. This evident long-term increase in the NDVI over these sensitive regions suggests that the vegetation in the sensitive regions had an important influence over northeast Asian dust activity during the years 1982-2006.

4. Influence of vegetation on dust activity

a. Dust load and transport

By using the CTRL simulations, the influence of vegetation on dust activity was measured. We first quantified the contribution of vegetation to the dust load and dust transport. The term "dust load" refers to the mass of dust in a unit atmospheric column (per unit area). Figure 2 depicts the annual variations of the NDVI and the dust load over the sensitive areas during the years 1982-2006. As seen in the figure, there was an evident negative correlation between the NDVI and the dust load on the interannual timescale; an anomalous high NDVI was accompanied by an anomalous low dust load. The correlation coefficient between them was −0.66 (significant at the 99% confidence level). A regression analysis shows that in these sensitive areas dust load was decreased by 2864 $\mu g\ m^{-2}$ for an increment of 0.1 in the NDVI. Also, the NDVI and the dust load in the sensitive regions had a negative correlation on the interdecadal timescale: a long-term increasing trend of the NDVI was associated with a long-term decreasing dust load. These opposite long-term trends of the NDVI and dust load indicated that the long-term decreasing dust load in the sensitive regions may be caused by the long-term increase of vegetation there.

By modulating dust emission, changes in vegetation have the ability to influence low tropospheric dust transport in the low troposphere, thereby affecting dust weather occurrence in the downwind regions (Gong *et al.*, 2003). To measure the influence of vegetation on dust transport in the low troposphere, the dust transport flux, i.e., the dust concentration multiplied by the wind speed, was computed. The vertically averaged dust transport flux was obtained in the low troposphere (0.90-0.78 sigma levels, approximately 1500 m height above ground level). This flux value was widely used to estimate the amount and direction of dust transport (e.g., Gong *et al.*, 2006; Zhao *et al.*, 2006). Here, by using the CTRL simulations, the dust transport flux was regressed against the average NDVI of the sensitive areas, and hence the influence of vegetation in the sensitive regions on the northeast Asian dust transport was quantified. Figure 3 shows the regression results. There are two major branches of anomalous dust transport flux: one stretches from eastern Mongolia to the regions northeastward, and the other flows across the south of northeastern China to Korea. These anomalous values suggested that the NDVI increase in the sensitive regions significantly reduced dust transport from southeastern Mongolia through the south of northeastern China to Korea, and minimized the dust transport from southeastern Mongolia to regions northeastward. Of all dust transport flux anomalies, the largest one was equal to 190.0 $\mu g\ m^{-2}\ s^{-1}$. Also, we analyzed the changes in surface dust transport flux (approximately 150 m above the ground level) induced by the NDVI variations in the sensitive areas (figure not shown). Our analysis shows that the dust transport anomalies mainly flowed from southeastern Mongolia across the south of northeastern China to Korea, which was similar to the south branch of the dust transport anomalies in the low troposphere (see Fig. 3). Of all the dust transport flux anomalies, the largest one was 5740 $\mu g\ m^{-2}\ s^{-1}$. In general, vegetation changes in the sensitive areas may have an impact on dust transport from the surface to the low troposphere; at the surface, there was a decreased amount of dust from the sensitive areas southeastward to the margins of these areas, but in the low troposphere, the amount of dust that flowed southeastward and northeastward was decreased.

b. Dust weather frequency

This subsection will discuss the influence of vegetation on the dust weather frequency. In the observational studies, dust events (e.g., dust storm, blowing dust, and floating dust) are defined by horizontal visibility. Here the definition of dust events used empirical relationships between dust events and the surface total suspended particles (TSP) metric (Song *et al.*, 2006) since dust modeling cannot produce horizontal visibility. These empirical relationships include dust storm (surface TSP $\geq 3000\ \mu g\ m^{-3}$), blowing dust (surface TSP $\geq 1200\ \mu g\ m^{-3}$), and floating dust (surface TSP $\geq 750\ \mu g\ m^{-3}$). It is worth noting that in this study surface dust concentration was chosen to classify dust events instead of surface TSP. For a given grid point, when its daily surface dust concentration exceeded 3000 $\mu g\ m^{-3}$, a dust storm was considered to have occurred at that grid point; if the daily surface dust concentration was between 1200 and 3000 $\mu g\ m^{-3}$ or between 1200 and 750 $\mu g\ m^{-3}$, a blowing dust or floating dust was recognized. Then, for each spring, we counted the number of days for each of the dust event categories (dust storms, blowing dust, and floating dust) for each grid point.

Three issues should be clarified with regard to this analysis: (1) why surface dust concentration was chosen to classify dust events, (2) how the deviations of dust weather frequencies were analyzed, and (3) uncertainty was caused by the criteria used to recognize dust events. With regard to the first issue, surface dust concentration rather than dust load was chosen to classify dust weather. This is because surface dust concentration, to a large extent, was affected by vegetation, but most dust variables including dust load were controlled by winds in the troposphere. Therefore, in order to highlight the influence of vegetation on the dust weather frequency, surface dust concentration was selected to identify dust weather. Regarding the second issue, the deviations of dust storm frequency (DSF), blowing dust frequency (BDF), and floating dust frequency (FDF) were obtained by subtracting the respective value in 2006 in each of the time series. Based on these deviations, the influence of vegetation on the dust weather frequency was examined. This is caused by the fact that in the CTRL experiment, the atmospheric conditions in each year were unchanged and set by using the corresponding values from 2006, although the vegetation was updated for each of the years. The dust weather frequencies for each of the years, retrieved from the CTRL experiment, were scattered around the value in 2006. Therefore, to clearly represent the influence of vegetation on dust weather frequency, the deviations of the DSF, BDF, and FDF were analyzed, respectively. According to the third issue, it is worth noting that there may occur some problems when the criteria were used in surface dust concentration to classify dust events, because these criteria were obtained by measurements of TSP rather than surface dust concentration, although they are positively correlated. It is obvious that the criteria defined by empirical relationships between dust events and surface dust concentration may be reasonable to be used here, however, it is beyond our current ability to derive these empirical relationships for surface dust concentration and dust events at this stage. More information on these relationships are required for a future work.

We first analyzed the spatial distributions of the anomalies of the dust weather frequency associated with vegetation changes. The result shows that the DSF decreased in eastern Mongolia, eastern northwest China, and the area to the south of northeastern China, as the NDVI increased (Fig. 4). According to the FDF, the regions where vegetation affects the BDF and FDF expanded, spreading from eastern northwest China, across the south of Mongolia, down to the region to the south of northeast China (Fig. 5). The spatial distribution of BDF anomalies associated with the NDVI changes was similar to that for the FDF (figure not shown). However, it is worth noting that, some regions had positive correlations between vegetation and the BDF and FDF, though most regions showed negative correlations between them. This positive correlation between vegetation and the BDF and FDF was caused by the decrease of the DSF. As vegetation increased, the DSF decreased, and hence the BDF and the FDF increased.

By averaging, we then analyzed the influence of vegetation on the dust weather frequency in the sensitive regions. The dust weather frequency in the sensitive regions is specified as an average of dust weather days of all grid points in the sensitive regions. Figure 6 shows the annual variations of dust weather frequency and the NDVI in the sensitive regions during the period from 1982 to 2006. The result indicates that the frequency of dust weather had evident decreasing trends, associated with the increasing trend of the NDVI. The correlation between dust weather frequency and the NDVI were −0.91, −0.66, and −0.13 for the DSF, BDF, and FDF, respectively. After screening out long-term trends from these time series, these correlations became a bit weaker, and they were then −0.85, −0.42, and 0.09 for the DSF, BDF, and FDF, respectively. The DSF and BDF correlations were significant at the 99% confidence level, while the FDF correlation was not. In addition, regression analysis between dust weather frequency and the NDVI were employed to measure the influence of vegetation on the dust weather frequency. The result shows that when the NDVI in the sensitive areas increased by 0.1, dust weather frequency decreased by 4.0 days/spring, 1.5 days/spring, and 0.2 days/spring for the DSF, the BDF, and the FDF in the sensitive regions, respectively. However, it is worth mentioning that in some years the NDVI was higher than that in 2006, but those years were associated with negative anomalies of the DSF and positive anomalies of the BDF and FDF. The positive anomalies of the BDF and FDF were caused by the decrease of the DSF, which increased the BDF and FDF. In general, on the interdecadal or interannual timescale, the increased vegetation in the sensitive area will evidently decrease

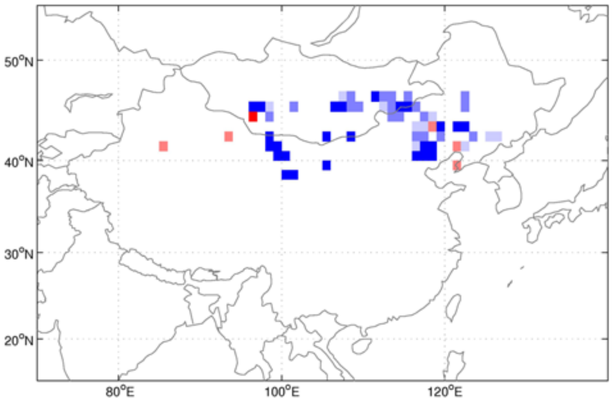

Fig. 4. Regression of dust storm frequency against the normalized deviation of vegetation index (NDVI). Blue (red) colors are for negative (positive) regression coefficients. The light, moderate, and heavy shadings indicate the anomaly of dust storm frequency increasing (decreasing) above (below) 0, 2, and 5, respectively, associated with an increment of the NDVI by 0.1.

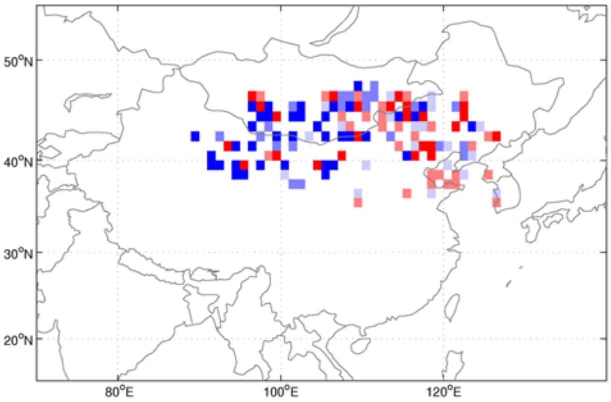

Fig. 5. Regression of anomaly of floating dust frequency against the NDVI. Blue (red) colors are for negative (positive) regression coefficients The light, moderate and heavy shadings indicate dust storm frequency increasing (decreasing) above (below) 0, 2, and 5, associated with an increment of 0.1 in the NDVI.

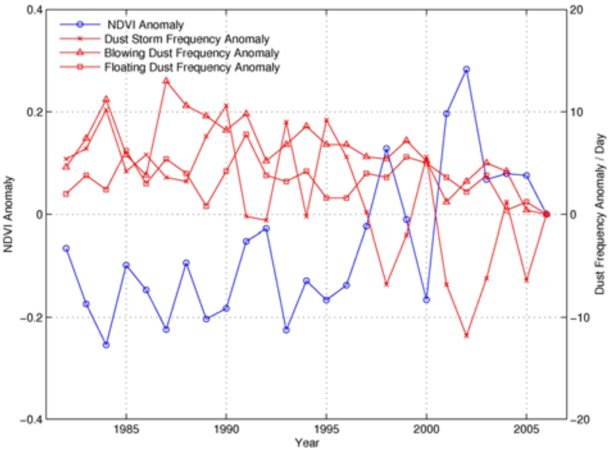

Fig. 6. The anomaly of spring dust weather frequency and spring NDVI in the sensitive regions, which were retrieved from the CTRL experiment.

the DSF and BDF; in contrast, it exerted a weak influence on the FDF.

5. Conclusion

In this study, the Integrated Wind Erosion Modeling System is used to examine the impact of vegetation on the northeast Asian dust activity during the years 1982-2006. Two model experiments are conducted: OBS versus CTRL experiments. The major findings show that there were sensitive regions where vegetation has a large potential to influence dust activity due to both high dust emission rate and large variations in vegetation coverage. These sensitive regions are located in southeastern Mongolia and central northern China (105°E-125°E and 38°N-48°N), with dust emission rates higher than 40 $\mu g\ m^{-2}\ s^{-1}$ and an NDVI between 0.1 and 0.3. At the surface, the vegetation in the sensitive regions effectively lessened the dust load on interannual and interdecadal timescales by reducing the amount of dust emission; the vegetation in the sensitive areas mainly decreased two branches of anomalous dust transport including one stretching from eastern Mongolia to the north and another flowing across the south of northeastern China to Korea. Moreover, on interdecadal or interannual timescales, the vegetation increase in the sensitive areas evidently decreased the dust storm frequency and the blowing dust frequency, but exerted a weak influence on the floating dust frequency. The correlations between dust weather frequency and the NDVI are −0.91, −0.66, and −0.13 for the dust storm frequency, blowing dust frequency, and floating dust frequency, respectively. When the NDVI increased in the sensitive areas by 0.1, the dust weather frequency in the sensitive regions decreased by 4.0 days/spring, 1.5 days/spring, and 0.2 days/spring for dust storm frequency, blowing dust frequency, and floating dust frequency, respectively.

Although this study has clarified the influence of vegetation on the northeastern Asian dust, it should be pointed out that the present results are obtained from 2006 atmospheric conditions. It is thought that our conclusions about the general trends should apply to other years. In addition, this study has not considered the diverse couplings of atmospheric conditions and vegetation, which displayed variable impacts of vegetation on dust activities. For example, the influence of vegetation on dust activity may be constrained by strong winds compared with that under weak wind conditions. We will consider these issues in a future study.

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REFERENCES

Carlson, T. N. and D. A. Ripley, 1997: On the relation between ndvi, fractional vegetation cover, and leaf area index. *Remote Sens. Environ.*, **62**, 241-252.

Chadwick, O. A., L. A. Derry, P. M. Vitousek, B. J. Huebert, and L. O. Hedin, 1999: Changing sources of nutrients during four million years of ecosystem development. *Nature*, **397**, 491-497.

Engelstaedter, S., K. E. Kohfeld, I. Tegen, and S. P. Harrison, 2003: Controls of dust emissions by vegetation and topographic depressions: An evaluation using dust storm frequency data. *Geophys. Res. Lett.,* **30**, 1294, doi:10.1029/2002GL016471.

Ganguly, S., M. A. Schull, A. Samanta, N. V. Shabanov, C. Milesi, R. R. Nemani, Y. Knyazikhin, and R. B. Myneni, 2008: Generating vegetation leaf area index earth system data record from multiple sensors. Part 1: Theory. *Remote Sens. Environ.*, **112**, 4333-4343.

Gong, S. L., X. Y. Zhang, T. L. Zhao, and L. A. Barrie, 2003: Sensitivity of Asian dust storm to natural and anthropogenic factors. *Geophys. Res. Lett.*, **31**, L07210, doi:10.1029/2004GL019502.

______, ______, ______, X. B. Zhang, L. A. Barrie, I. G. McKendry, and C. S. Zhao, 2006: A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part II: Interannual variability and climate connections. *J. Climate*, **19**, 104-122.

Gutman, G., and A. Ignatov, 1998: The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. *Int. J. Remote Sens.*, **19**, 1533-1543.

Lee, E. H., and B. J. Sohn, 2009: Examining the impact of wind and surface vegetation on the Asian dust occurrence over three classified source regions. *J. Geophys. Res.*, **114**, D06205, doi:10.1029/2008JD010687.

Mao, R., C. H. Ho, Y. Shao, D. Y. Gong, and J. Kim, 2011a: Influence of arctic oscillation on dust activity over Northeast Asia in the Integrated wind erosion modeling system. *Atmos. Environ.*, **45**, 326-337.

______, D. Y. Gong, J. D. Bao, and Y. D. Fan, 2011b: Possible influence of arctic oscillation on dust storm frequency in North China. *J. of Geographical Sciences*, **21**, 207-218.

Natsagdorj, L., D. Jugder, and Y. S. Chung, 2003: Analysis of dust storms observed in Mongolia during 1937-1999. *Atmos. Environ.*, **37**, 1401-1411.

Shao, Y., 2001: A model for mineral dust emission. *J. Geophys. Res.*, **106**(D17), 20239-20254.

______, and Coauthors, 2003: Northeast Asian dust storms: Real-time numerical prediction and validation. *J. Geophys. Res.*, **108**(D22), 4691, doi:10.1029/2003JD003667.

Shinoda M., J. Gillies, M. Mikami, and Y. Shao, 2011: Temperate grasslands as a dust source: Knowledge, uncertainties, and challenges. *Aeolian Res.*, **3**, 271-293.

Song Z. X., J. Y. Wang, and S. G. Wang, 2007: Quantitative classification of northeast Asian dust events. *J. Geophys. Res.*, **112**, D04211, doi: 10.1029/2006JD007048.

Sugimoto N., Y. Hara, K. Yumimoto, I. Uno, M. Nishikawa, and J. Dulam, 2010: Dust emission estimated with an assimilated dust transport model using lidar network data and vegetation growth in the Gobi desert in Mongolia. *SOLA*, **6**, doi: 10.2151/sola2010-032.

Tegen, I., A. A. Lacis, I. Fung, 1996: The influence on climate forcing of mineral aerosols from disturbed soils. *Nature*, **380**, 419-422.

______, S. P. Harrison, K. Kohfeld, I. C. Prentice, M. Coe, and M. Heimann, 2002: Impact of vegetation and preferential source areas on global dust aerosol: Results from a model study. *J. Geophys. Res.,* **107**, 4576, doi:10.1029/2001JD000963.

Tucker, C. J., J. E. Pinzon, M. E. Brown, D. A. Slayback, E. W. Pak, R. Mahoney, E. F. Vermote, and N. El. Saleous, 2005: An extended

AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *Int. J. Remote Sens.*, **26**, 4485-4498.

Zhao, T. L., S. L. Gong, X. Y. Zhang, J. P. Blanchet, I. G. McKendry, and Z. J. Zhou, 2006: A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part I: Mean climate and validation. *J. Climate*, **19**, 88-103.

Zhou, Z. J., and G. C. Zhang, 2003: Typical severe dust storms in northern China during 1954-2002. *Chinese Science Bulletin*, **48**, 2366-2370.

Zou, X. K., and P. M. Zhai, 2004: Relationship between vegetation coverage and spring dust storms over northern China. *J. Geophys. Res.*, **109**, D03104, doi: 10.1029/2003JD003913.