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Possible effects of climate change of wind on aerosol variation during winter in Shanghai, China

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ABSTRACT

Several data sets were introduced to investigate the possible effects of climate-change-related variation of wind on aerosol concentration during winter in Shanghai, China. These data sets included the daily wind speed, wind direction, visibility, and precipitation from 1956 to 2010, hourly PM_{10} concentration from 2008 to 2010, and the NCEP/NCAR reanalysis data of global atmospheric circulation from 1956 to 2010. The trend of aerosol concentration and its correlations with wind speed and wind direction in winter were analyzed. Results indicated that there was an increase in the number of haze days in winter of 2.1 days/decade. Aerosol concentration, represented by PM_{10} in this study, was highly correlated to both wind speed and direction in winter. The PM_{10} concentration increased as wind speed decreased, reaching maximum values under static wind conditions. The PM_{10} concentration was relatively lower under easterly winds and higher under westerly winds. The analysis showed that weaker East Asia winter monsoons have resulted in a reduction of wind speed, increase in static wind frequency, and decline in the frequency of northerly winds since the 1980s. Moreover, the rapid expansion of urban construction in Shanghai has changed the underlying surface considerably, which has led to a reduction in wind speed. Finally, a wind factor was defined to estimate the combined effects of wind speed and wind direction on aerosol concentrations in Shanghai. The analysis of this factor indicated that changes in atmosphere circulation and urbanization have had important effects on the number of winter haze days in Shanghai.

Introduction

Atmospheric aerosols include both natural and anthropogenic aerosols. The study by Zheng, Luo, Zhao, Chen, and Kang (2012) shows that the major aerosols in Eastern China are anthropogenic, and satellite measurements show that there is an increasing trend of aerosol optical depth (AOD) in the Shanghai region, suggesting that anthropogenic emissions are increasing significantly (Luo, Lu, Li, & Zhou, 2000).

In addition to increased emissions, many studies have indicated that aerosol pollution events are closely related to meteorological conditions (Wang, Lin, Cai, & Chen, 2008; Yang, Wang, & Huang, 1994; Zhou, Qi, Gan, & Gao, 2010), and that the effect of meteorological conditions on aerosol concentrations has a short time scale (days–week) (Tie, Geng, Peng, Gao, & Zhao, 2009). Ke and Tang (2007) studied the aerosol scattering coefficient in Beijing in both autumn and winter, and their results showed that wind direction had considerable impact on the aerosol scatting coefficient. For example, the southwesterly wind led to an increase in the aerosol scattering coefficient, whereas the northeasterly wind produced a reduction. The study by Qiu, Sheng, Fang, and Gao (2004) suggests that southerly wind conditions result in an increase in the AOD in Qingdao, enhancing the scattering of solar radiation. Work by Xu, Geng, Zhen, and Gao (2010) shows that different surface winds lead to distinctively different effects on the diffusion and transportation of aerosols. The aerosol scattering coefficient decreases with wind speed when the prevalent wind direction is easterly; however, the converse is true under the effect of westerly winds. Additionally, Xu et al. (2005) proposed that the pollution diffusion process in urban regions might form a local downwind "plume" effect, enhancing the regional aerosol influence due to climatic characteristics of local

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Fig. 1. Map of Shanghai and nearby cities.

dynamic effects. Furthermore, the study by Song and Lu (2006) suggests that the AOD of aerosols in Shanghai reaches a maximum in summer and a minimum in spring. Seasonal differences in ground visibility show good consistency with the above features of atmospheric aerosols, which has been proven by other related research (Lei, Zhang, He, & Streets, 2011; Luo, Lu, Zhou, Li, & He, 2001; Streets et al., 2008).

However, few studies have focused on the changes of urban climate on the aerosol concentrations in Shanghai, especially in winter, which is the most polluted season. During winter, the frequency of precipitation is low, and wind speed and direction play important roles in controlling the local air pollution (Zhang, Zhen, Tan, & Yin, 2010). In this study, we analyze the effects of long-term changes in wind speed and direction on aerosol pollution in Shanghai during winter.

Data and methodology

Meteorological and aerosol data

Shanghai is a coastal megacity with an average altitude of 4 m. It is one of the biggest cities within the region of the East Asia monsoon, although there are many large- and medium-sized cities to its west. It is bordered by Jiangsu and Zhejiang provinces to the west and by the East China Sea to the east (Fig. 1). The geographical environment results in the local meteorological conditions having significant influence on aerosol concentrations over Shanghai.

The hourly concentrations of PM_{10} in winter (Dec–Feb) and the corresponding data on wind speed and direction between 2008 and 2010 were analyzed. The data were collected at Pudong Station (31°14′ N, 121°32′ E). To focus on the impact of wind on aerosol pollution, days with precipitation were excluded from the analysis. Historical daily measurements of wind speed and direction from 1956 to 2010 were used to investigate the long-term characteristics of winds in Shanghai. The number of haze days was estimated using measurements of relative humidity, visibility, and precipitation data. The emission data of dust and concentrations of SO_2 and NO_2 were obtained from the Shanghai Environment Monitoring Center. Additionally, reanalysis data from NCEP/NCAR (US National Centers for Environmental Prediction/US National Center for Atmospheric Research) with spatial resolution of $2.5° \times 2.5°$ were used to study the general circulation patterns. The atmospheric circulation characteristic index (used for the parameter of meridional circulation) from the National Climate Center of China Meteorological Administration was also applied in the study. The remote sensing data from Chinese Academy of Sciences Data Center for resources and Environmental Sciences.

PM_{10} concentrations were measured using a GRIMM-180 Stationary Aerosol Monitor (GRIMM Technologies, Inc., Germany) with precision of $1\,\mu g/m^3$ and a flow rate of 72 L/h, which was calibrated periodically and properly maintained. Contact anemorumbometer, precipitation gauge, and psychrometer were applied to measure meteorological elements until 1999, and the MILOS 500 auto weather station (Vaisala Inc., Finland) has been implemented since 2000. Parallel observational experiments were performed for two years to evaluate the quality and ensure the consistency of the data; this was executed to the standards of the China Meteorological Administration (CMA). Visibility and weather phenomena were recorded by weather observers using the CMA specifications for ground observation (China Meteorological Administration, 2003).

Statistical methods

The statistics analysis system (SAS) was used for the normal distribution test. The Spearman correlation analysis of the hourly PM_{10} concentrations and wind speed, long-term trend of PM_{10}, wind direction, and wind speed in Shanghai was analyzed using linear regression. The Mann–Kendall method (Fu & Wang, 1992) (with confidence of 0.05) was applied to detect the wind mutation. Following the method of Li and Fang (2005), the Siberian high-pressure index (SHPI) and the East Asian winter monsoon intensity index (EAWMII), using the NCEP/NCAR reanalysis data, were calculated by analyzing sea surface pressure. The correlation of these indices with wind speed and direction were calculated to obtain insight into the relationship between large general circulations and local winds.

The detailed methodology for calculating the SHPI and EAWMII are as follows. The SHPI can be obtained by calculating the average sea level pressure (ASLP) within the region 40–60° N (j = 53–61) and 75–115° E (i = 31–47) in Eq. (1):

$$\mathrm{ASLP} = \frac{\sum_{i=31,47,j=53,61} \mathrm{SLP}_{i,j}}{(47-31+1)(61-53+1)}. \tag{1}$$

The EAWMII (in Eq. (2)) is calculated as follows: (a) calculate the sea level pressure (SLP) difference between 120° E and 150° E (i.e., subscripts 1 and 2), (b) normalize the values (i.e., superscript * in Eq. (2)) and calculate the sum within 30–60° N (i.e., j = 49–61), and (c) normalize again (i.e., superscript **). In Eq. (2), t = 1–55 represents the years from 1956 to 2010. The normalizing operator in Eq. (2)