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A heavy haze episode in Beijing in February of 2014: Characteristics, origins and implications

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ABSTRACT

More than half Chinese cities are suffering from severe air pollution due to the rapid development of industry and urbanization. Beijing, as a political and cultural center of China, has frequently suffered from severe haze. However, the precise sources of air pollution in Beijing still remain uncertain. In this study, the observational data ($PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2) at ten monitoring stations from February 8 to 28, 2014, in Beijing were used to analyze air pollution. The satellite observations for aerosol optical thickness were also used. Backward trajectory model and receptor models were used to identify the sources of air pollution in Beijing. On the basis of $PM_{2.5}$ concentrations, we separated the whole data into three categories: relatively clean air ($PM_{2.5}$ concentrations less than 75 μg m^{-3}), haze ($PM_{2.5}$ concentrations greater than 75 μg m^{-3} but less than 200 μg m^{-3}) and heavy haze ($PM_{2.5}$ concentrations greater than 200 μg m^{-3}). The results show that the average concentrations of $PM_{2.5}$ are 29.5 μg m^{-3}, 136.6 μg m^{-3} and 311.2 μg m^{-3} for relatively clean air, haze and heavy haze cases, respectively. The back trajectory cluster analysis reveals that the predominant clusters are east and south for the heavy haze case. The results of the receptor models show that for the haze case, pollutants mainly originated from south of Beijing such as Dezhou, Liaocheng and Heze in Shandong province, while for the heavy haze case, pollutants were mainly from southwest of Beijing such as Baoding, Hengshui and Handan in Hebei province. These results indicate that the emissions in the surrounding provinces made a significant contribution to Beijing's air pollution. Thus, it is necessary to implement air pollution control for all surrounding areas, especially for the industrial zones in the south/southwest regions of Beijing.

Keywords: *Air pollution, haze, trajectories model, cluster analysis, sources*

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1. Introduction

As a developing country, China has achieved rapid economic development over the past few decades. However, its success was accompanied by environmental deterioration, including air, water and soil pollutions. In recent years, air pollution has become the most serious environmental problem in China (Chan and Yao, 2008). Researches show that more than two–thirds of urban areas in China do not meet China's national ambient air quality standards (secondary daily national air quality standard for $PM_{2.5}$ is 75 μg m^{-3}) (Hao and Wang, 2005; Shao et al., 2006). Although many megacities in the world have also suffered from air pollution, the composition of air pollution in China is particularly complicated. Coal is a major source of energy in China, accounting for about 70% of the total energy consumption. Emissions from coal combustion are the main cause of China's air pollution (Hao et al., 2007; Chan and Yao, 2008). With rapidly increasing in vehicle numbers, vehicle emissions are becoming important for urban pollution (Hao et al., 2007). The source of air pollution in Chinese megacities has gradually shifted from conventional coal combustion to a mixture of coal combustion and vehicle emissions. One of the major air pollutants is particulate matter (PM), particularly fine particles ($PM_{2.5}$) (i.e., PM with an aerodynamic diameter less than 2.5 μm), which is mostly responsible for the formation of the regional haze (the day with visibility <10 km under the conditions of 80 % relative humidity (RH)) in China. In most Chinese cities, $PM_{2.5}$ concentrations are much higher than the World Health Organization (WHO) Air Quality Guidelines of 10 μg m^{-3} (annual average) and 25 μg m^{-3} (daily average) (WHO, 2005). Severe air pollution affects not only human health, regional and global climates, but also the economic development and social progress (Yu, 2000; Yu et al., 2000; Yu et al., 2001a; Yu et al., 2001b; Shao et al. 2006; Chan and Yao, 2008; Zhang, 2008; Yu, 2014; Yu et al., 2014a; Yu et al., 2014b; Yu et al., 2014c). Although many studies about the air pollution and haze–fog in China have been carried out, the reasons of heavy haze formation for many cities still remain an issue of uncertainty. Air pollution problems in China's megacities will continue to be an important topic of environmental issues in the coming decades.

Beijing, the political and cultural center of China, is one of the largest cities in the world and also is the China's second most populous city with an urban population 20.6 million over an area of about 16 410 square kilometers. $PM_{2.5}$ in Beijing is abnormally elevated, and often rising to more than 100 μg m^{-3}. According to the government statistics, the $PM_{2.5}$ concentrations in only eight days are less than 75 μg m^{-3} (National Air Quality Secondary Standard) in January 2013. The latest results show that the severe haze pollution episodes in megacities were driven to a large extent by secondary aerosol formation, which contributed 50% of $PM_{2.5}$ in Beijing (Huang et al., 2014). On the other hand, Guo et al. (2014) found that photochemical oxidation of VOCs and NO_X from urban traffic emissions and SO_2 from regional industrial sources are primarily responsible for the periodic cycles of severe haze episodes in Beijing on the basis of comprehensive atmospheric measurements from 25 September to 14 November 2013. In addition, Beijing is a city sensitive to regional transport of aerosols from its surrounding provinces. According to Bergin et al. (2005), some pollutants can be regionally transported over hundreds or thousands of kilometers, long enough to cross provincial, national, and even continental boundaries. Due to the unique topography and meteorology, atmospheric pollutants from the surrounding

areas are also significantly important to the air pollution formation in Beijing (Chen et al., 2007). Wang et al. (2010) pointed out that the most serious PM_{10} pollution in Beijing can be attributed to the pollution emissions in the southwestern regions. The result of $PM_{2.5}$ source apportionment shows that the major aerosol components in Beijing may primarily come from the southern region (Zhang et al., 2013).

In recent years, air mass trajectory model, cluster analysis, potential source contribution function (PSCF) and concentration weighted trajectory (CWT) methods have been widely used to assess the prevailing transport pathways and the source regions of air pollutants (Wang et al., 2004; Wang et al., 2010; Liu et al., 2013; Zhang et al., 2013; Yu et al., 2014c). Beijing had suffered from severe haze from February 21 to 27, 2014, that is the longest time of heavy haze after carrying out air quality monitoring under new air quality standard since January 1, 2013. In this work, we analyzed the air pollution in Beijing from February 8 to February 28, 2014, using the surface and satellite observational data. Meanwhile, the air mass back trajectory and receptor models (PSCF and CWT) were used to study the possible impact of local and transport pollutant sources on the formation of haze in Beijing before and during the haze episode.

2. Methodology

2.1. Observational data

Hourly air pollutants ($PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2) at 10 urban monitoring stations (Wanshouxigong (39.87°N, 116.37°E), Changpinzhen (40.20°N, 116.23°E), Nongzhanguan (39.97°N, 116.47°E), Tiantan (39.87°N, 116.43°E), Guanyuan (39.94°N, 116.36°E), Haidianquwanliu (39.99°N, 116.315°E), Dongsi (39.95°N, 116.43°E), Gucheng(39.93°N, 116.23°E), Shunyixincheng (40.1438 N, 116.72°E), Aotizhongxin (40.00°N, 116.41°E)) in Beijing were measured with the standard methods (CNEMC, 2013). The China National Environ-mental Monitoring Center (CNEMC) has started to release the real–time hourly concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2 at 496 national monitoring stations in 74 major cities in China since January 2013. These 10 urban monitoring stations in Beijing belong to part of them. The more detailed information about the observational data can be found in the website of Ministry of Environmental Protection in China (ARL, 2015). In addition, the aerosol optical depth (AOD) data at 550 nm obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) was used in this study. MODIS instrument aboard the Terra (EOS AM) spacecraft passes from north to south across the equator in the morning. Because the effective satellite daily data over the study region are relatively scarce, we mainly elected MOD08_D3 data (Level–3 data) with a 1° spatial resolution from February 8 to 28, 2014.

2.2. Air mass back trajectory calculation, clustering analysis, PSCF and CWT

Following Yu et al. (2014c), the 48 h back trajectories starting at the arrival level of 100 m from the 10 urban monitoring sites in Beijing were calculated with the NOAA HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php) to study the possible impact of local and transport sources on the formation of haze in Beijing during the study period (February 8 to February 28, 2014). Since the 10 monitoring sites are very close, the trajectory clusters method is used for all sites as a whole. In this work, we used the angular distance to do cluster analysis. The method used to calculate the mean angle distance between two trajectories was adapted from Sirois and Bottenheim (1995). The NCEP/FNL (National Centers for Environmental Prediction, Final Analyses) fields obtained from NOAA available every 3 h with a spatial resolution of 0.5×0.5 were used as meteorological data input to the model. Based on the meteorological fields, the backward trajectory model was run eight times per day at starting times of 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 LT (local time) (16:00, 19:00, 22:00, 01:00, 04:00, 07:00, 10:00 and 13:00 UTC, respectively).

Based on the results of the HYSPLIT model, the PSCF method can be used to identify the probable locations of emission sources which affect pollutant loadings at the receptor site (Hsu et al., 2003). The PSCF values for the grid cells in the study domain are calculated by counting the trajectory segment endpoints that terminate within each cell at the measurement time. The PSCF value for the cell (*i,j*) is defined as (Ashbaugh et al., 1985; Wang et al., 2009):

$$PSCF_{ij} = \frac{m_{ij}}{n_{ij}} \quad (1)$$

where, n_{ij} represents total number of the trajectory segment endpoints at the grid cell (*i,j*), and m_{ij} is the number of the trajectory segment endpoints at the grid cell (*i,j*) with $PM_{2.5}$ concentrations higher than an arbitrarily set criterion. $PM_{2.5}$ criterion is set to 75 μg m^{-3} for the polluted concentration in this study. The cells with high PSCF values are indicative of the areas that have high potential contributions to the high pollutant concentrations at the receptor site. A limitation of the PSCF method is that grid cells may have the same PSCF value when the pollutant concentrations are only slightly higher or extremely higher than the criterion. To compensate the limitation, a concentration weighted trajectory (CWT) method was used to calculate the trajectory weighted concentration. The CWT method calculated the average weighted concentration C_{ij} for the grid cell (*i,j*) as follows (Hsu et al., 2003; Wang et al., 2009):

$$C_{ij} = \frac{1}{\sum_{i=1}^{M} T_{ijl}} \sum_{l=1}^{M} C_l \; T_{ijl} \quad (2)$$

where, *l* and *M* represent the index and total number of the trajectories, respectively. C_l is the concentration observed at the receptor site on the arrival of trajectory *l*. T_{ijl} is the time spent in the grid cell (*i,j*) by trajectory *l*. A high C_{ij} value implies that the air parcels traveling over the grid cell (*i,j*) would be associated with high polluted values at the receptor site.

3. Results and Discussion

3.1. Characteristics of the heavy haze episode in Beijing

Extremely severe and persistent haze has frequently occurred in Beijing since 2012, and concentrations of $PM_{2.5}$ on hourly average are often record–breaking. Figure 1 shows the temporal variations of hourly $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3 observed at the ten sites in Beijing from February 8 to 28, 2014. The results at these 10 sites were analyzed together as a whole because the $PM_{2.5}$ concentrations at the ten monitoring sites are close as shown in Figure 1. Generally, the concentrations of air pollutants like $PM_{2.5}$, PM_{10}, SO_2, CO and NO_2 had the same trends of change during this period, with the exception of O_3. The O_3 concentrations show obvious diurnal variations for the whole period with values below 100 μg m^{-3}, much lower than the China hourly national air quality standard of 200 μg m^{-3}. The SO_2, NO_2 and CO concentrations during this period ranged from 1 to 207 μg m^{-3}, 2 to 263 μg $m^{-3}$and 0.1 to 9.8 mg m^{-3}, respectively, which are much lower than the corresponding hourly national air quality standard (500 μg m^{-3} for SO_2, 200 μg m^{-3} for NO_2 and 10.0 mg m^{-3} for CO) in most of the times. The NO_2 concentrations with values higher than 200 μg m^{-3} are mainly occurred during the heavy haze period from 24 to 27 February. Because SO_2, NO_2 and CO are emitted directly from biomass, fuel and coal burning, their concentrations can be affected more significantly by the local sources.