Atmospheric Pollution Research 5 (2014) 528-538

Atmospheric Pollution Research

www.atmospolres.com

Formation and dominant factors of haze pollution over Beijing and its peripheral areas in winter

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ABSTRACT

The formation process and dominant factors of air pollution over Beijing and its immediate vicinities, known as a rapidly developed agglomeration, were dissected and analyzed in multi–scale in this paper. Several severe haze pollution events occurred over northern China in October, November 2013, during which time a set of hourly sampling data, including four air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2) from 35 monitoring stations, as well as relevant vertical profiles of meteorological parameters were collected. Two major formation processes were found to be contributing to two substantial different pollution types in Beijing area. One type was characterized by stagnant weather conditions with moderate southerly winds. Air pollutants from local and southern industrial provinces accumulated and $PM_{2.5}$ concentrations were less than 250 μg/m^3, with a duration of 1 or 2 days. In contrast, the second type was characterized by intense temperature inversion under planetary boundary layer (PBL) and natural dusts in the middle and upper part of PBL transported from Gobi Desert cover the fine particle like a "lid", making the regional atmospheric layers extremely stable. Consequently, $PM_{2.5}$ concentrations exceeded 400 μg/m^3 and the severe pollution can last for 3 to 5 days. Moreover, domestic heating is a significant contributor to haze pollution in winter. Its role was estimated using comparative methods as it began in the middle of observing period. Statistical results showed that domestic heating contributed to the increase in most of the monitored air pollutants, especially for SO_2. Spatial interpolation and overlay analysis were conducted to get the spatial features of domestic heating–induced pollutants in order to clarify its sources. Population distribution data was integrated into a spatial statistical analysis, which indicated the concentrations of $PM_{2.5}$ and SO_2 have no or even negative relationship with population, thus revealing pollutants from domestic heating in Beijing were mainly from suburban areas without central heating systems.

Keywords: *Urban air pollution, spatiotemporal analysis, domestic heating, temperature inversion, particle transportation*

doi: 10.5094/APR.2014.062

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Article History:
Received: 19 December 2013
Revised: 01 April 2014
Accepted: 01 April 2014

1. Introduction

Beijing and its peripheral areas have experienced a rapid increasing of urbanization. Urban population, energy consumption, increasing number of vehicles, has contributed to the situation of gradually exacerbation of atmospheric pollution (Akimoto, 2003; Chan and Yao, 2008; Fu, 2008; Marshall et al., 2008; Ma et al., 2010; Zhang et al., 2012). Since once occurred in notoriously foggy London, frequent episodes of regional haze pollution have occurred in major cities over Northern China (Sun et al., 2006; Wang et al., 2013), especially in megalopolis agglomeration centralized with Beijing (Liu et al., 2013). The dominant pollutant, particulate matter, particularly $PM_{2.5}$ in haze pollution, is epidemiologically associated with the risk of deleterious health effects on cardiovascular and lung diseases (Du et al., 2010; Qiu et al., 2013). Besides, dominant northwestern winds in cold days, especially in spring, transported natural dust from Northwestern China to the east of China, resulting in dust storms in Beijing with the PM_{10} concentration more than 1 mg/m^3 (Sugimoto et al., 2003; Liu et al., 2008). Domestic heating in winter contributes to a higher emission of air pollutants, causing heavy regional air pollution when stagnant weather condition prevails (Duan et al., 2006). All these air pollution sources in Beijing can be divided in to two categories: local emission and regional transport.

A large amount of case studies have been carried out to investigate the main sources and formation processes of local urban air pollution (Hao et al., 2005; Guo et al., 2010; Li et al., 2011). Based on the local emissions inventory, Hao et al. (2005) found that vehicular emissions contributed about 74% to the ground level NO_X and 28% of PM_{10}, while industrial sources occupied 13% and 49%, respectively. Domestic heating in Beijing, starting in November ending in the following March was the major source for SO_2 during winter season (Meng et al., 2008). Using MM5–CAMx model, Huang et al. (2012) pointed out that heating and industrial emission sources contributed 66.1% to the total SO_2 concentration. However, heavy industries were relocated out of Beijing and central heating system gradually replaced the scattered winter coal–fired heating in planning for Beijing 2008 Olympic Games (Beijing Municipal Bureau of Statistics, 2013), which significantly altered the local emission system. There are few studies concerning the recent domestic heating effects, especially for its spatial features and contributions in major pollutants. Moreover, some studies have pointed out the topography of Beijing that surrounded by mountains on two sides, in the north the Yanshan Mountain, and in the west the Xishan Mountain. These mountains make the local pollutants difficult to be driven away unless strong winds arrive (Zhang et al., 2013). Other studies have indicated that many tall buildings recently constructed are unfavorable for the dispersion of locally accumulated pollutants (Liu et al., 2005). However, these analyses mainly focused on the pollution events horizontally with discrete monitoring stations near surface. Vertical variations of meteorological factors, i.e., temperature, wind power and direction, relative humidity play an important role in the formation process of local air pollution (Tao et al., 2014).

Regional transport of atmospheric pollutants has been a focus of many studies over Beijing and its immediate vicinities (Liu et al., 2008; Li et al., 2013; Tao et al., 2014). Dust storms are recognized to be one of the main regional transportation events that prevailing northwesterly wind carried large amounts of suspended dust from Gobi deserts to downstream regions including Beijing area during cold days, leading to high PM_{10} concentrations and low visibility (Liu et al., 2008). Since different sizes of atmospheric particles may come from different sources, the ratio, $PM_{2.5}/PM_{10}$ has been widely used for recognizing their sources (Chan et al., 2005; Yu et al., 2006). By one case in Beijing, Sun et al. (2006) suggested that high ratios (larger than 0.6) were generally attributed to secondary particle formation with high relative humidity, whereas low ratios were attributed to the long–distance transport of dust. However, this method may suffer from the uncertainties in particle concentration measurements (He et al., 2001). Model simulations suggest that pollutants transported between city clusters contribute substantially to the formation of regional large–scale pollution events (Li et al., 2013). Based on Model–3/CMAQ, Streets et al. (2007) indicated that about 34% of $PM_{2.5}$ concentrations came from industrial sources outside of Beijing, including Heibei province and Tianjin Municipality. Huang et al. (2010) estimated that the total emission source contribution ratio (ESCR) from these regions is 26.65%. Although these kind of regional air quality models are capable of providing atmospheric chemistry profiles with high quality, they cannot simulate accurately if some input data are not appropriate and reliable (Lee et al., 2011).

During winter season in 2013, several severe haze pollution events happened over Beijing and its peripheral areas. Beijing Environmental Protection Bureau released twice yellow alerts of haze pollution (BJ–EPB, 2013). Few studies have discussed the mechanism and formation process of haze pollution in winter, especially the diffusion/mixing phenomenon and lid effects between metropolises with four kinds of major air pollutants as well as vertical profiles of meteorological data. Furthermore, bounding the role of domestic heating in this process is of great importance to comprehensively understand the regional atmospheric environment and urbanization. By the end of 2012, BJ–EPB has published hourly monitoring data of six pollutants from 35 monitoring stations which cover almost every district (county level) of Beijing. In this study, using the above described data as well as vertical profiles of meteorological parameters, we made a synthesized analysis on a series of regional haze pollution events over Beijing and its peripheral areas during winter season in 2013. On the basis of fully understanding the mechanism and formation process of different haze events, we categorized them into two groups according to their causes. Particularly, contributions of air pollutants from domestic heating were calculated as it began exactly in the middle of our observing period. With interpolation and overlay analysis, we got the spatial features of domestic heating–induced pollutants and revealed the dominant causes of these emissions. The main purpose of the article is to study the formation process and dominant factors of regional air pollution over city agglomeration in winter.

2. Data and Methods

2.1. Data collection

Hourly air pollutants data. There are 35 air pollution monitoring sites, evenly distributed in Beijing, which have been established by BJ–EPB (Figure 1b). The hourly concentration data of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, CO) were obtained by each monitoring station automatically. From Jan 2013, BJ–EPB gradually published these real–time data to the public. We collected a dataset for one month, ranging from 14 October 2013 to 16 November 2013 from Beijing Municipal Environmental Monitoring Center (BJ–EPB, 2013). In order to analyze the local anthropogenic emissions and monitor regional transport process, we selected 9 monitoring sites, with 3 sites (number 28, 29, 30) in southern rural regions near Heibei province and Tianjin Municipality (Figure 1a), 3 sites (number 1, 2, 31) in central urban area, and 3 sites (number 22, 23, 25) in northern rural regions near mountains. Thirty five stations were used for the interpolations presented in Figure 10, but only 9 of them were used for the analysis presented in Figures 3 and 9. The average hourly concentrations of observing pollutants in each group were compared and all the data met the accuracy standard of China.

Census data. The latest population census data (6th population census of China) was used in our study. There are six districts in urban area: Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan, with the latest total urban population of 11 950 124. In order to make an accurate analysis, street–level districts were selected as the appropriate experimental geographic units. According to the Beijing Administrative Districts Atlas, we digitalized every boundary of the district and major roads, matching each of census data within urban area of Beijing to the administrative map in ArcInfo 10. Ultimately, 134 geographic census units were filled with corresponding census data, perimeter, and area in their attribute table.

Meteorological data. Meteorological data including temperature, relative humidity, wind speed and direction were obtained for the same period from the China Weather Website Platform (CMA, 2013) which is maintained by China Meteorological Bureau. In particular, vertical profiles of aforementioned meteorological parameters in Beijing can be found on the Wyoming Weather Web (UW, 2013). The location of meteorological station in Beijing has been marked in Figure 1b (Station No. 0) and the collection time for these data is 12:00 a.m.

2.2. Spatial interpolation method

The monitoring sites were spatially discontinuous, we needed to transform the discrete point into a surface data to investigate the domestic heating effects on the spatial pattern of pollutants over an entire map. Here, we used ordinary Kriging (OK) method to interpolate spatially the evenly distributed concentrations of pollutants. Kriging is one of the most commonly used spatial interpolation methods in a variety of fields (Bayraktar and Turalioglu, 2005) which allows generating a linear estimator that does not need prior knowledge of the stationary mean of the observed values (Pang et al., 2010). Moreover, the distribution of 35 monitoring sites in Beijing is relatively uniform (Figure 1b), thus, the precision of interpolation can be guaranteed.

3. Results and Discussion

3.1. Formation process of haze events over Beijing and its peripheral areas in winter

Figure 2 shows the hourly variations of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2) from an urban road monitoring site (number 34) in Beijing. During observing period, there have been 8 obvious air pollution events (marked in Figure 2) with different pollution levels. Peak values of $PM_{2.5}$ concentrations were about 250 $\mu g/m^3$ in common air pollutions, while severe haze events nearly reached 450 $\mu g/m^3$. Domestic heating began on November 1, exactly in the middle of observing period, which played a significant role in wintertime air pollution. Compared to air pollution in spring (Tao et al., 2014) and autumn (Liu et al., 2013), haze events in winter were rather heavier. We found two types of haze pollution in Beijing and its peripheral areas according to the concentrations of particulate matter and gaseous pollutants. Pollution type–1 (event 2, 5, 6, 7, 8) lasted for 1 or 2 days with the $PM_{2.5}$ concentrations less than 250 $\mu g/m^3$. In contrast, $PM_{2.5}$ concentration even exceeded 400 $\mu g/m^3$ in type–2 pollution (event 1, 3, 4), with durations of 3 to 5 days. In both types of haze pollution, variations of gaseous pollutants were positively correlated with particulate matter, while in type–2 pollutions, the magnitudes of particulate matter were much greater than the gaseous pollutants.