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Formation mechanism of continuous extreme haze episodes in the megacity Beijing, China, in January 2013

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ABSTRACT

The primary objective of this study is to investigate the formation and evolution mechanism of the regional haze in Beijing by analyzing the process of a severe haze episode that occurredfrom1 to 31 January 2013. The mass concentration of $PM_{2.5}$ and its chemical components were simultaneously measured at the Beijing urban atmospheric environmental monitoring station. The haze was characterized by a high frequency, a long duration, a large influential region and an extremely high $PM_{2.5}$ values (>500 μg/m^3). The primary factors driving the haze formation were stationary atmospheric flows (in both vertical and horizontal directions), while a temperature inversion, a lower planetary boundary layer and a higher RH accelerated the formation of the regional haze. In one incident, the temperature inversion layer occurred at a height of 130 m above ground level, which prevented the air pollutants from being dispersed vertically. The regional transport of pollutants also played an important role in the formation of the haze. Wind from the south of Beijing increased from 58% in January 2012 to 63% in January 2013. Because the area to the south of Beijing is characterized by high industrial development, the unusual wind direction favored the regional transport of pollutants and severely exacerbated the haze. SO_4^{2-}, NO_3^- and NH_4^+ are the three major water-soluble ions that contributed to the formation of the haze. The high variability in Cl^- and K^+ indicated that large quantities of coal combustion and biomass burning occurred during the haze.

1. Introduction

Aerosols negatively affect climate change, human health and atmospheric visibility and have become a major issue in China (Tan et al., 2009a,b; Liu et al., 2012; Duan and Tan, 2013; Tao et al., 2014a,b). In a vertical direction, aerosols scatter (Cahill, 1996) and absorb (Jacobson, 2001) solar and terrestrial radiation, changing the thermal balance of the troposphere. In a horizontal direction, aerosols scatter and absorb light and reduce visibility, which can result in a depressive effect on humans because of the gray sky color (Hyslop, 2009) and can increase traffic hazards in the sky and on the ground (Mukherjee and Viswanathan, 2001). Coarse particles (i.e., particulate matter with an aerodynamic diameter greater than 10 μm) settle readily on the ground because of gravity, while the fine particles remain floating and can easily enter the body through the respiratory system (Peters et al., 1997; Schwartz and Neas, 2000). Ultrafine particles (i.e., particulate matter with an aerodynamic diameter equal to or less than 50 nm) are able to penetrate the lungs and circulatory system, producing negative effects on the cardiovascular (Bai et al., 2007; Carlsten et al., 2007) and immune systems (Diaz-Sanchez et al., 1999; Kang et al., 2010) and possibly the

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nervous system Furthermore, many studies have demonstrated that fine particles, referred to as $PM_{2.5}$ (i.e., particulate matter with an aerodynamic diameter equal to or less than 2.5 μm), that contain high concentrations of toxic and hazard substances are related to morbidity and mortality levels (Miller et al., 2007; Araujo et al., 2008; Brook et al., 2010). Moreover, aerosols have a negative effect on agricultural productivity (Chameides et al., 1999).

The rapid economic growth in China since the 1980s has resulted in high emissions of atmospheric pollutants that have reduced air quality (Guo et al., 2011). In the 1990s, the Chinese government spent billions of Yuan to combat environmental pollution, especially during period prior to the 2008 Olympic Games (Streets et al., 2007; Zhou et al., 2010). While some progress was made (Cheng et al., 2013), the trend of poor air quality continued after 2008. Hazes have occurred frequently in China during the last decade (Wang et al., 2006; Kan et al., 2007; Li et al., 2010; Duan et al., 2012; Liu et al., 2012; Xu et al., 2013). A haze is defined as a weather condition in which the horizontal visibility is less than 10 km and the RH is less than 90% (Wu et al., 2007). Fine aerosol particles (i.e., $PM_{2.5}$) play a dominant role in the formation and evolution of haze (Liu et al., 2013).

There are four major areas in China with severe haze pollution: the Jing-Jin-Ji Region, the Yangtze River Delta, the Pearl River Delta (PRD) and the Sichuan Basin (Zhang et al., 2012). The first three regions are rapidly developing economic areas with high pollutant emission levels. Under calm meteorological conditions, a haze forms readily. The geography of Sichuan Basin does not favor the diffusion of pollutants and the higher RH in this region, which can favor the formation of hazes (Chen and Xie, 2013). The concentration of $PM_{2.5}$ varies seasonally, generally remaining at a relatively low value in the summer and autumn and increasing in the winter and spring (Chang et al., 2009). The high $PM_{2.5}$ emissions in the winter and early spring result from the large amounts of coal that are burned to provide heat in northern China (Ma et al., 2011). There is regional variation in the air pollution in China; northern China has a more severe aerosol problem than southern China (Zhang, et al., 2012). This can be attributed to the wide spread heating in northern China in winter and the lower rainfall in this area compared with southern China. In addition, the aerosol problem in eastern China is worse than western China because of the high levels of industrial and traffic emissions. Particulate pollution is becoming increasingly serious in China (Massie et al., 2004; Ramanathan et al., 2005), illustrating the importance and urgency of reducing the atmospheric pollution.

An unprecedented haze incident occurred in China in January 2013. The high frequency, high $PM_{2.5}$ values, extended duration and large area of the haze have rarely been previously reported. The maximum instantaneous $PM_{2.5}$ value was higher than 500 $\mu g/m^3$, and over 75% of the time, a haze condition was observed. During the most severe period, northern, southern, eastern and middle China were influenced by the haze. The characteristics and formation mechanisms of these extreme haze events have been reported by many other studies. An atmospheric circulation pattern in the middle troposphere over Eurasia was found to have undergone a long wave adjustment, which provided the meteorological background for haze development (Wang et al., 2014). Northwest winds in high altitudes with dust particles on the top boundary layer met southerly airflows, which not only transport industry pollutants to Beijing but also cause widespread haze pollution when moist air masses exist (Tao et al., 2014d). Aerosol particles in southern air masses were especially rich in inorganic and oxidized organic species, whereas northern air masses contained a large fraction of primary species (Zhang et al., 2014). Because the O_3 concentration was low during the haze, fast conversion from the gas phase of NOx and SO_2 to the particle phase of NO_3^- and SO_4^{2-} indicated the importance of heterogeneous formation of NO_3^- and SO_4^{2-} on haze formation (Quan et al., 2014). Stagnant meteorological conditions, coal combustion, secondary production and regional transport are regarded as the four major factors driving the formation and evolution of the hazes (Ji et al., 2014; Sun et al., 2014). However, the characteristics of $PM_{2.5}$ distribution all over the Beijing region in January 2013 and the reasons driving this distribution are not provided. Additionally, the influence of planetary boundary layer (PBL) on the $PM_{2.5}$ concentration and haze formation were not investigated.

2. Experiment

2.1. Experimental site

All measurements were conducted in Beijing, the capital of the People's Republic of China and the national center for politics and culture. The gross domestic product (GDP) of Beijing in 2012 was 0.3 trillion dollars with a growth rate of 7.7% (http://www.bjstats.gov.cn/xwgb/tjgb/ndgb/201302/t20130207_243837.htm). The city's population is 20 million, and its population density at the end of 2012 was 1261 people per km^2. Beijing's total energy consumption was 71.8 million tons of standard coal, and there were 5.2 million cars with a growth rate of 3% as of 2012 (http://www.bjstats.gov.cn/xwgb/tjgb/ndgb/201302/t20130207_243837.htm). High levels of energy consumption and the high economic status have resulted in increased emissions of air pollutants in Beijing.

Field measurements were conducted from 1 to 31 January 2013 at the urban atmospheric environmental monitoring station (39.96°N, 116.36°E) on the campus of Beijing Normal University (BNU), which is located in the northern part of Beijing and is ~300 m south of the third ring road that acts as one of the main traffic routes in Beijing. The observation site was located on the roof of a six-floor building (~20 m above ground level). All instruments were installed in an air-conditioned room except for the visibility sensor, which was installed outdoors.

2.2. Measurements and methods

The $PM_{2.5}$ mass concentration was measured using a tapered element oscillating microbalance (TEOM, RP1405F, USA) at 35 sites in Beijing that were monitored by the Beijing Environmental Bureau (http://www.cnpm25.cn/city/beijing.html) and the site at BNU in this study. The visibility was measured using a visibility sensor (Belfort 6000, USA), which consisted of a transmitter, a receiver and a controller, and had a range of 10 m to 50 km (Liu et al., 2013). The wind direction, wind speed, and relative humidity were monitored at the meteorological station (Vaisala, Finland). A ground-based microwave radiometer (MP-3000A, USA) was used to detect the real-time atmospheric temperature and RH profile. The detection cycle of