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An analysis of chemical and meteorological characteristics of haze events in the Seoul metropolitan area during January 12–18, 2013

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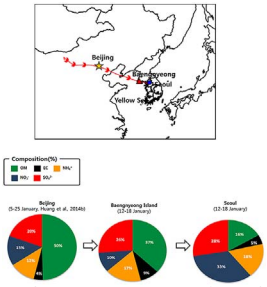
GRAPHICAL ABSTRACT



Back trajectory starting from the Seoul supersite at 17 LST on January 12, 2013 with 6 h interval and 500 m release height and chemical composition changes along the long-range transport path from Beijing→ Baengnyeong Island → Seoul during the haze event of January 2013.

1. Introduction

Haze is an atmospheric phenomenon caused by the interaction of fog, dust, smoke, and various types of particulate matter (PM) that obscure the clarity of the sky (Chen et al., 2008; Fu and Chen, 2017; Huang et al., 2014a; Ji et al., 2014). They result in poor visibility of just a few kilometers and adverse public health effects that damage people's respiratory and cardiovascular systems (Koken et al., 2003; Harrison et al., 2012; Chen et al., 2013; Burnett et al., 2014). Haze resulting from anthropogenic primary and secondary formed aerosols also has adverse effects on natural and agricultural ecosystems and weather and climate changes (Seinfeld and Pandis, 2006; Shen et al., 2015; Wang and Chen, 2016).

Looking at the world's air pollution history, such hazes have been an inherent pollution problem in the early stages of development in countries when rapid industrialization and urbanization without proper emission controls has increased air pollutant emissions above the acceptable limits of environmental capacity (Seinfeld, 2004; Huang et al., 2014b). China has suffered from severe haze problems for several decades, and extreme haze events have occurred frequently in China since 2013 (Huang et al., 2014a; Fu and Chen, 2017). An extremely heavy, record-breaking haze event occurred on January 10–15, 2013, over eastern and northern China, and hourly $PM_{2.5}$ concentrations reached more than 700 μg/m^3 (Ji et al., 2014; Quan et al., 2014). This extraordinary haze event created great interest in scientific society, and many studies have been conducted to understand the main causes of haze events. The key characteristics of the chemical species (Huang et al., 2014a, b; Wei et al., 2014), anomalies of the meteorological conditions (Wang et al., 2014b, 2014e), and the formation mechanisms (Tao et al., 2014; Wang et al., 2014a, c, d; Zhang et al., 2014; Zheng et al., 2015) were studied. These are the first essential steps in creating proper emission control strategies to improve haze problems.

Huang et al. (2014b) investigated the chemical nature and sources of particulate matter at four urban sites across China using state-of-the-art analytical measurements and statistical techniques, and they reported that the severe haze pollution was mainly driven by secondary organic and inorganic aerosols. The largest contribution of chemical species of $PM_{2.5}$ during the high PM episode of January 5–25, 2013, in Beijing was organic matter (OM) at 40.7% followed by sulfate (16%), nitrate (12%), ammonium (9.8%), and elemental carbons (EC). Fossil fuel combustion and biomass burning are the main sources inducing the PM episode in China (Huang et al., 2014b). The most up-to-date

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comprehensive review paper of Fu and Chen (2017) summarized the key features and formation mechanisms of secondary aerosols during haze events in China, including during the January haze of 2013, as well as China's strategies for controlling severe haze pollution. According to their summaries, the high burden of particulate and gaseous precursor emissions, adverse meteorological conditions, and the excessive formation of secondary inorganic aerosols are generally the main reasons inducing the severe haze in China.

Using observations or model assessments, previous studies showed that haze events in South Korea are largely dependent on the LRT from China as well as on stagnant meteorological conditions. Lee et al. (2011b, 2013) demonstrated that the LRT from China and the stagnant high pressure system over Korea were the main reasons for the haze event in the SMA. Kim et al. (2016a) reported that the high pressure system over southern China caused the regional high PM problem and frontal movement along the eastward or southeastward induced the LRT from China to Korea. Koo et al. (2008) simulated aerosol transport over the East Asian region using Community Multi-scale Air Quality Mode (CMAQ) and concluded that PM_{10} transport from China to Korea was significant, with its contribution reaching up to 80% during the high PM episode period. Koo et al. (2012, 2015) also demonstrated that the LRT from China initiated the PM episode in the SMA, while local emissions made the air quality worse. Oh et al. (2015) reported that the LRT of the polluted air masses was a possible cause of a multiday PM_{10} episode during the cold season from 2001 to 2013 in the SMA. Park et al. (2013a,b) simulated a high PM_{10} episode during January 10–16, 2013 using the CMAQ, and demonstrated that LRT from northeastern China to Korea was the main reason for the haze episode in the SMA during January 2013. Kim et al. (2017) simulated that the LRT of PM_{10} and $PM_{2.5}$ from China to the SMA during the PM episode of late February 2014 were 64% and 70%, respectively.

The haze event in the SMA started on January 12, 2013 with an hourly peak $PM_{2.5}$ level of 156 μg/m^3. The haze event in the SMA started with a one- or two-day time lag after the occurrence of the record-breaking haze event during January 10–20 in the BTH area. It was initiated by the LRT of aerosols and gaseous precursors formed in northern China along the northwest wind, and it then became worse through the addition of local emissions, due to the limited ventilation of airflows in the SMA. The present study was conducted to determine the meteorological and chemical characteristics of the haze event of January 12–18, 2013, using intense chemical species measurements at the Baengnyeong and Seoul supersites as well as available Light Detection and Ranging (LIDAR) and weather observations in Korea. Two supersites measuring chemical species of $PM_{2.5}$ and gaseous precursors were aligned on the path of the LRT from northeastern China to Seoul via Baengnyeong Island, which is located in the Yellow Sea between the Korean Peninsula and eastern China. This was a special event to detect the direct impact of the LRT haze plume from the BTH area to the Baengnyeong Island and then to Seoul.

This study is of interest to identify the similarities between northern Chinese and SMA haze events that occurred sequentially during January 12–18, 2013, what the changes in aerosol chemical properties were during the LRT from China to the SMA, what roles local emission sources played, and finally, what would be the proper strategies to reduce haze events in the SMA. Although many studies have been carried out to understand the physical and chemical properties of the January 2013 haze events in China and Korea, to the authors' best knowledge, few studies have been conducted to determine changes in aerosol chemical properties during the LRT from China to Korea and to determine the roles of local emissions in the LRT during the high PM episode in the SMA. This study will also be helpful in understanding the secondary aerosol formation mechanism and then in creating an effective air quality control policy and abatement plan for the SMA.

2. Methodology

The haze episode during January 12–18, 2013, was analyzed using measurements of chemical species and precursor pollutants, LIDAR, and meteorology in Korea, especially focusing on the SMA. Detailed descriptions follow.

2.1. Observational sites

The locations of the Baengnyeong and Seoul supersites, the LIDAR station, and the weather monitoring stations in the SMA are shown in Fig. 1. The Baengnyeong supersite (37°57′N, 124°37′E) is on Baengnyeong Island, located in the far western part of the Korean Peninsula, in the Yellow Sea between China and Korea and approximately 180 km from the Chinese Shandong Peninsula. The Seoul supersite (37°36′N 126°56′E) is located in the northwestern part of Seoul (Lee et al., 2012). The Korea National Institute of Environmental Research (NIER) designed the Baengnyeong supersite to measure the regional background concentrations from eastern China and the Seoul supersite to monitor the local concentrations in Seoul. Under northwesterly wind conditions, the polluted air mass that originated in the northern China was transported to Seoul via Baengnyeong Island. These supersites were designed to identify the effects of LRT on air quality in Korea and to understand the formation mechanisms of secondary aerosols in the atmosphere during the LRT.

The hourly meteorological observations of wind speed and direction, temperature, relative humidity, solar radiation, and visibility are measured at the Seoul weather monitoring station and the Baengnyeong weather station, both part of the Korea Meteorological Administration (KMA). Aerosol optical properties in Seoul are continuously monitored with the Raman and Backscatter LIDAR system located at Seoul National University (37°28′N, 126°57′E) in the southeastern area of Seoul.

2.2. In-situ monitoring of aerosol mass and chemical composition

The Korean Ministry of Environment established an intensive air pollution monitoring program in 2007 to understand the physicochemical characteristics of long-range transported and locally emitted aerosols by benchmarking the US EPA Supersite program (Solomon and Sioutas, 2008). Although NIER actually operates and monitors five supersites in Korea, only the Seoul and Baengnyeong supersites were chosen for this study.

The mass and chemical compositions of $PM_{2.5}$ were continuously monitored at the supersites in Korea. Continuous monitoring of PM and its chemical species was conducted in parallel using various instruments mounted with a cyclone or impactor. BAM1020 (MetOne Ins.) using a β-ray attenuation method was continuously operated to measure $PM_{2.5}$ mass concentrations at 1-h intervals. An ambient ion monitor (URG-9000B, URG Co.) and ion chromatography (Dionex, DX-1 000) connected with the IonPac AS14A and the CS12A column were used for real-time measurements of water-soluble inorganic ions such as SO_4^{2-}, NO_3^-, NH_4^+, and Ca^{2+}. The sampling interval employed for this study was typically about 30 min. The detection limit of this ion monitoring system is 0.02 μg/m^3.

The mass concentrations of OC and EC were thermally measured at intervals of 1 h by a semi-continuous carbon analyzer developed by Sunset Laboratory. The US National Institute for Occupational Safety and Health (NIOSH) Method 5 040 and the evolved gas TOT method were modified for the continuous measurement of OC and BC in $PM_{2.5}$ samples. The modified method uses a shorter, more simplified analysis time in order to increase the sampling time. It should be mentioned that traditionally the DRI analyzer uses reflectance (TOR) correction and the Sunset Laboratory instrument uses the transmission (TOT) correction, but both instruments have currently installed dual optics where simultaneous TOR and TOT corrections are possible (Karanasiou et al.,