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Vertical observation and analysis on rapid formation and evolutionary mechanisms of a prolonged haze episode over central-eastern China

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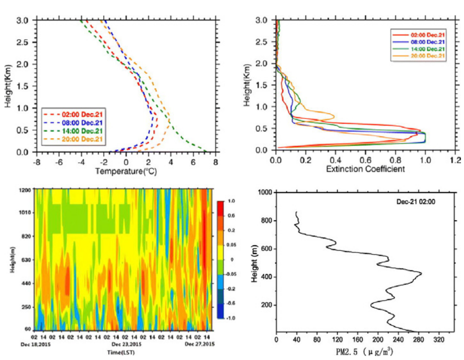
HIGHLIGHTS

- Vertical profiles of light extinction coefficient and $PM_{2.5}$ were observed.
- Vertical transport leads to the increase of $PM_{2.5}$ concentration at ground level.
- The $PM_{2.5}$ high-concentration layer stretched upward to approximately 400 m.
- Easterly and northerly winds decreased the pollution level partially.

GRAPHICAL ABSTRACT



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ABSTRACT

To clarify the rapid formation and evolutionary mechanisms of an extremely severe and persistent haze and fog (HF) episode that occurred in central-eastern China from Dec 20 to 25, 2015, a novel campaign was conducted and vertical profiles of wind, temperature, light extinction coefficient (LEC) and $PM_{2.5}$ concentration were used to analyze the rapid formation and evolutionary mechanisms of this HF episode. The substantial downward transportation of regional pollution from high layers and stagnant weather conditions favorable for the local pollution accumulation were the two main causes of the rapid increase in pollutant concentration. Southwest wind speeds of 4 m/s between 300 and 600 m and obvious downward flows were observed, whereas the southwest wind speeds were low below 300 m, and strong temperature inversion with intensity of 4.5 °C/100 m expanded vertically to a height of 600 m. Two peaks of $PM_{2.5}$ concentration were observed at 200 and 700 m, corresponding to 235 and 215 μg/m^3, respectively. The frequent change in wind direction and wind speeds resulted in the fluctuation of $PM_{2.5}$ concentration. The turbulence within lower layers of the troposphere was enhanced by easterly and northerly winds which decreased the pollution level; however, the strength and stretching height of the winds were insufficient to fully clear the air of pollutants. The $PM_{2.5}$ concentration revealed 2-high concentration layers in the vertical direction. The maximum concentration layer was below 100 m, while the second high-concentration layer was at 400 m.

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Fig. 1. Location of the field campaign. The red triangles represent the location of the Longshun Manor site and Xiqing meteorological station, while the yellow dots represent typical cities in the Jing-Jin-Ji region: Beijing, Tianjin and Cangzhou. The figure on the right depicts the tethered balloon field campaign site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1. Introduction

With the rapid economic development and urbanization, aerosol pollution in northeastern China has attracted broad attention from both the public and government (Quan et al., 2011, 2014; Ji et al., 2014; Huang et al., 2012). High concentrations of fine particulate ($PM_{2.5}$) not only cause substantially reduced visibility by scattering and absorbing sunlight (Zhang et al., 2015; Han et al., 2012), also shown to have detrimental effects on human health (Tie et al., 2009). Extensive studies have been conducted in recent years to investigate the sources and formation mechanisms of sever haze episodes in northern China (Han et al., 2015; Sun et al., 2015; Zhao et al., 2013; Zheng et al., 2016a, 2016b). Researchers indicated that the fundamental cause of severe haze episodes was the emissions of massive amount of pollutants, and as such developed a new inventory of air pollutant emissions in Asia in the year of 2006 to support the Intercontinental Chemical Transport Experiment-Phase B (INTEXB) (Zhang et al., 2009). $PM_{2.5}$ pollution was not only a local but also a regional issue. It was found that local emissions contributed only 15.4% to $PM_{2.5}$ concentrations, while 40.7% came from the surrounding areas, and the remaining 42.7% originated from regional transportation in more distant areas (Chen et al., 2017). Another view was that the secondary inorganic species were the dominant contributors to the high $PM_{2.5}$ concentration in Northern China (Zheng et al., 2016a, 2016b). Accumulation of the high $PM_{2.5}$ mass concentration was accompanied by a continuous size growth from the nucleation-mode particles to yield numerous larger particles (Guo et al., 2014). In addition to the pollution sources, unfavorable meteorological conditions led to the accumulation of pollutants and the formation of the secondary aerosols (Han et al., 2014; Sun et al., 2014; Tang et al., 2016).

During the former haze episodes, the $PM_{2.5}$ concentration was less than 50 $\mu g \cdot m^{-3}$ (clean) at the beginning of each cycle and reached several hundred micrograms per cubic meter (polluted) within 2–4 days (Han et al., 2014; Guo et al., 2014). With the recent continuous heavy pollution process, the $PM_{2.5}$ concentration rapidly increased to approximately several hundred micrograms per cubic meter in a short time (Sun et al., 2016). It was aimed to determine the other mechanisms, in addition to atmospheric chemistry, led to the rapid growth of pollutant concentration during the HF event. As for the cleaning mechanism, in addition to the cold air, researchers also indicated that fog had capacity to scavenge fine particles during severe haze episodes (Wang et al., 2014), other mitigation mechanism should be considered during the heavy pollution events. Most of the previous studies mainly focused on the characteristics of haze pollution on the surface layer (Wu et al., 2015; Wang et al., 2016; Yang et al., 2015), the structural characteristics of the atmospheric boundary layer and the role in the haze formation and mitigation mechanisms still merit further research (Li et al., 2012). An aerosol Lidar system was used to determine the vertical distribution of aerosols, and the vertical aerosol extinction coefficient had a different form owing to the influence of the aerosols from various sources (Zhang et al., 2015).

Tianjin is one of the core cities in the Jing-Jin-Ji region, which is the most severely polluted region in China. Previous studies have examined the vertical distribution of haze and fog episodes in Tianjin city based on 255 m tower (Han et al., 2009; Shi et al., 2012; Tian et al., 2013; Zhang et al., 2011). However, little is known about vertical variation of $PM_{2.5}$ in the lower troposphere. Additionally, given that Tianjin is located on the west coast of Bohai, the physical and chemical characteristics of aerosols were also influenced by easterly winds coming off of the sea. In this paper, an intensive field campaign was conducted during an extremely severe and persistent haze and fog (HF) episode that occurred in Tianjin

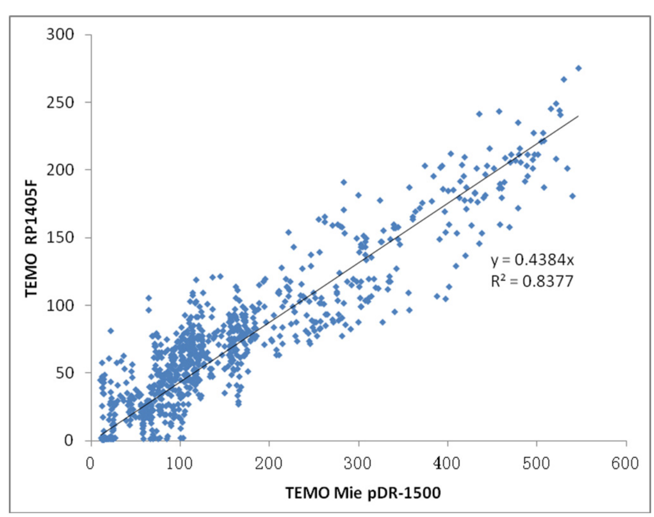

Fig. 2. Comparison of $PM_{2.5}$ concentrations measured by TEMO Mie pDR-1500 and TEMO RP1405F.

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