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The characteristics of abnormal wintertime pollution events in the Jing-Jin-Ji region and its relationships with meteorological factors

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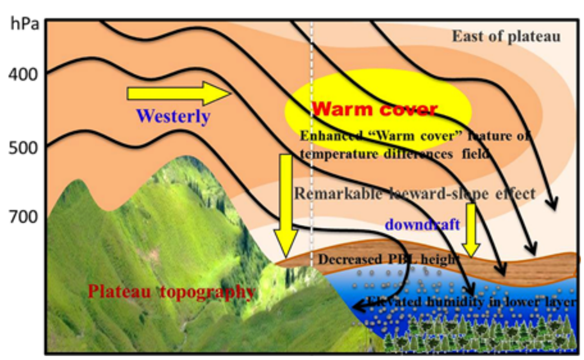
HIGHLIGHTS

- Air pollution rebounded in winter 2016 in the Jing-Jin-Ji region.
- The semi-enclosed terrain enhanced wintertime "downdraft".
- Remarkable "warm cover" structure characterized the middle troposphere.
- Abnormally low PBL height were observed during pollution episodes.
- An aggregative model was established.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite the implementation of strict air pollution control measures in recent years, severe haze events were still encountered in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) region during the winter 2016. In this work, seasonal differences in correlations between air pollution and geographic terrain, atmospheric dynamical and thermal structures, and PBL height over the Jing-Jin-Ji region in history and recent years were investigated and a comprehensive model of atmospheric factors affecting winter air pollution formation was proposed. We found that the distribution of $PM_{2.5}$ concentration closely correlated with the topography feature of China and the difference in haze pollution intensity between winter and other seasons was the most significant in the Jing-Jin-Ji region. The "semi-enclosed" terrain along with the enhanced winter "downdraft" strongly inhibited the diffusion and convection of air pollutants in this region. Meanwhile, seasonal variations of the vertical thermal structure over the Jing-Jin-Ji region, i.e., the anomalous pattern of "upper warming and bottom cooling" structure in the middle troposphere, and the "weak wind zone" were more distinct in winter 2016 than historical record, providing an important precondition for the frequent occurrence of thermal inversion layers and severe pollution episodes in the lower troposphere. In addition, abnormally low PBL heights occurred in the Jing-Jin-Ji region during severe pollutant episodes in winter 2016, with mean postmeridian PBL height in December of only 869.4 m, the minimum value since 2013. $PM_{2.5}$ concentration was not only closely related to PBL height but also the "warm cover" structure in the middle troposphere. The stronger the structure was, the lower the PBL height became, and severer the pollution event was encountered, accompanying water vapor accumulation and intensification of the thermal inversion layer in the lower troposphere. All above observations revealed the mutual feedback correlations between air pollutants concentration and meteorological factors.

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1. Introduction

With the rapid industrialization and urbanization in recent decades, severe air pollution and heavy haze events occurred frequently and continue to spread in China (Wu, 2012). Air pollution is shifting from a coal-burning-dominated type in the last century to a coal-vehicle-mixed-pollution, trans-regional and compound type in China (Chan and Yao, 2008; Fu et al., 2001). The regions to the East of 100°E and south of 40°N in China is often subject to heavy haze events, including the Pearl River Delta, most of Northern China, Eastern China and Central China (Fu and Dan, 2014). Since the 1990s, with ever increasing enhancement of pollutant emissions in China, the heavy pollution season has extended from winter to spring, autumn and summer (Xu et al., 2015). In recent years, $PM_{2.5}$ particles have become the primary pollutant during severe pollution events in China's large and medium-size cities (Cao, 2014) and have turned into one of the most prominent environmental issues, affecting air quality, regional and global climates (Jacobson, 2001; Wang et al., 2014a), and human health (Brunekreef and Holgate, 1999; Shi et al., 2017). Haze pollution events have threatened the sustainable economic development in China and have drawn serious international concerns (Brunekreef and Holgate, 1999; Jacobson, 2001; Wang et al., 2014b; Xin et al., 2012). After the implementation of the "Action plan for air pollution prevention and control", Beijing, Tianjin and Hebei have successively come up with the corresponding action plans, deployed and implemented various measures to prevent and control air pollution (Bai, 2014; He et al., 2013). According to the Chinese statistical yearbook of 2010–2016 on environment analysis, the total amount of SO_2 and NO_x emissions in the Jing-Jin-Ji region have decreased by 21.6% and 26.1% respectively from 2011 to 2015. Based on data retrieved from observations of the Ozone Monitoring Instrument (OMI) from 2005 to 2015, NO_x emissions over 48 Chinese cities have decreased by 21% from 2011 to 2015 (Liu et al., 2017), and a 50% reduction of SO_2 has been observed from 2012 to 2015 in the North China Plain, one of the most severe SO_2 polluted region in the world (Krotkov et al., 2016).

However, despite of the reduction of primary air pollutants emissions, long-lasting severe pollution episodes also erupted over the Jing-Jin-Ji region in winter 2016. Five widespread and persistent pollution episodes were encountered in December 2016 alone. The most severe pollution episode occurred during the evening of December 29, 2016, with the highest peak $PM_{2.5}$ mass concentration of >500 μg m^{-3} in Beijing. The air quality have reached "heavily polluted" level, i.e., daily mean $PM_{2.5}$ > 150 μg m^{-3}, a standard established by the Ministry of Environmental Protection of China (MEPC, HJ6333-2012) and even "severely polluted" level, i.e., daily mean $PM_{2.5}$ > 250 μg m^{-3} (MEPC, HJ6333-2012), in some areas. This pollution event featured long duration, wide-range influence, rapid development and strong intensity. The $PM_{2.5}$ concentration showed an explosive and sustained growth, leading to a continuous degradation in visibility. By January 7, 2017, the pollution situation was alleviated, benefitting from a favorable atmospheric diffusion condition. However, statistical analysis showed that $PM_{2.5}$ concentration in spring, summer and autumn gradually decreased in the Jing-Jin-Ji region from 2013 to 2016, and even the wintertime pollution in this area also showed a downward trend from 2013 to 2015. It is noteworthy that these long-lasting extreme pollution episodes occurred in winter 2016 was rather counterintuitive with respect to the evident decreasing trend in $PM_{2.5}$ concentration in recent years. Enlightened by the above anomalous feature in air pollution annual changes, it is necessary to further explore the seasonal particularity of air pollution in the Jing-Jin-Ji region and the comprehensive influence mechanism of meteorological factors in winter.

The potential effects of emissions reduction and the results of many current researches have demonstrated that although the regional air pollution mainly depends on primary emission sources, atmospheric circulation conditions, such as the wind field, stratification conditions, water vapor, temperature and precipitation, may also be crucial for the formation of severe air pollution (Huang et al., 2016; Liu et al., 2016; Wei et al., 2015; Zhang et al., 2014; Zhang et al., 2016). Furthermore, climate change provides another vital context to further aggravate air pollutions (Cai et al., 2017; Shen et al., 2016). Particularly, air pollutions in China show clear seasonal variation and regional features affected by complex topography (Gao, 2008; Sun et al., 2013; Tao et al., 2014; Xu et al., 2005). The PBL height is an important meteorological factor that affects the vertical diffusion of atmospheric pollutants and water vapor concentrations. Hence, PBL height plays an important role on the formation, accumulation, and dissipation of heavy pollution (Li et al., 2015; Ren et al., 2004; Tang et al., 2016; Wang et al., 2015b). When the development of turbulent diffusion was restrained, the PBL height was highly decreased and the atmospheric convective diffusion was thus significantly weakened. Meanwhile, water vapor accumulated in the lower troposphere facilitated the formation of severer air pollutions (Du et al., 2014; Wang et al., 2015a). Therefore, a comprehensive analysis on extreme wintertime air pollution events in the Jing-Jin-Ji region was carried out in this work to reveal the underlying causes of severe air pollutions in the winter and an aggregative model was established accordingly.

2. Data sets

To understand the characteristics of air pollutants in the Beijing area and around China, long-term observation data sets of aerosols were acquired from January 2013 to February 2017. The mass concentration of common air pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2 and O_3) were provided by the MEPC (Ministry of Environmental Protection of China) with a temporal resolution of 1 h. There are 1497 air pollution monitoring stations in 31 provinces of China. It is worth noting that the number of monitoring station has increased from about 670 in 2013 to 946 in 2014 and reached 1493 in 2015. The numbers of stations in the Jing-Jin-Ji region and the Beijing area remain 80 and 12 Table 1, respectively. The monthly conventional meteorological data including temperature, RH, haze days and visibility from 2416 observation stations across China within the 1951–2015 period were quality controlled and assured by the National Meteorological Information Center. Monthly reanalyzed meteorological data of the PBL height, temperature, wind and relative humidity from 1979 to 2015 and daily PBL height data from January 2016 to February 2017 were obtained from ERA-interim on the ECMWF website (https://www.ecmwf.int/). Boundary layer height is defined here as the level, where the bulk Richardson number, with reference to the lowest model level, reaches the critical value of 0.25 (European Center for Medium-Range Weather Forecasting, 2006).

The L-band sounding system of the meteorological observation network consists of a secondary radar on the ground and a GTS1 digital radiosonde and uses the same distance measurement technique as a secondary windfinding radar. It can automatically determine the meteorological elements such as air pressure, temperature, humidity, wind direction and wind speed. The GTS1 radiosonde has a sampling resolution of 1.2 s and a vertical resolution of 8 m and more detailed description is provided by Li et al. (2009) and Cai et al. (2014). There are 120 sounding stations nationwide that can provide informative "seconds level" data, "minutes level" data and traditional air pressure layer probe data with high vertical resolution. The geographic position of the Beijing sounding station is located in the Daxing district (39.80°N and 116.467°E), with an elevation of approximately 330 m. The "seconds level" radiosonde data from January 2010 to February 2017 used in this work were collected at 14:00 Beijing Time (BJT) in the morning and at 20:00 BJT in the evening on a daily basis. Preliminary quality control has been applied to the L-band sounding "seconds level" data before analysis, and interpolation was implemented in a vertical direction at an interval of 5 hPa. In addition, since no intensive L-band sounding measurements were conducted at 14:00 BJT in winter, results of the European Central reanalysis at 14:00 BJT were used instead to analyze the PBL height variation. For better inter-comparison with radiosonde