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Elucidating the relationship between aerosol concentration and summertime boundary layer structure in central China☆

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ABSTRACT

Wuhan, a megacity in central China, suffers from frequent aerosol pollution and is accompanied by meteorological factors at both synoptic and local scales. Partly due to the lack of appropriate observations of planetary boundary layer (PBL), the associations between synoptic conditions, PBL, and pollution there are not yet fully understood. Thus, systematic analyses were conducted using the fine-resolution soundings, surface meteorological measurements, and aerosol observations in Wuhan during summer for the period 2013–2016, in combination with T-mode principal component analysis and simulations of backward trajectory. The results showed that the variations of boundary layer height (BLH) not only modulated the diurnal variation of $PM_{2.5}$ concentration in Wuhan, but also the daily pollution level. Five different synoptic patterns during summer in Wuhan were identified from reanalysis geopotential height fields. Among these synoptic patterns, two types characterized by northeasterly prevailing winds, were found to be associated with heavy pollution in Wuhan. Driven by the northeasterly winds, the polluted air mass from the heavily polluted regions could be easily transported to Wuhan, such as North China Plain and Yangtze River Delta. Such regional transports of pollutants must be partly responsible for the aerosol pollution in Wuhan. In addition, these two synoptic patterns were also featured by the relatively high cloud cover and low boundary layer height in Wuhan, which would favor the occurrence of pollution there. Overall, this study has important implications for understanding the important roles of meteorological factors in modulating aerosol pollution in central China.

1. Introduction

In past decades, the rapid urbanization and industrialization in China (Shou and Zhang, 2012; Yan et al., 2016) have led to frequent aerosol pollution (Guo et al., 2011, 2013; San Martini et al., 2015; Zhang and Cao, 2015; Qin et al., 2017). Thus, great efforts have been devoted to the air quality issues (e.g., Chen et al., 2016; Zhang et al., 2010; Liu et al., 2011; Wang et al., 2014; Li et al., 2016; Wu et al., 2016; Guo et al., 2016a; Miao et al., 2017a). Previous studies have revealed that the anthropogenic emissions are the fundamental cause of aerosol pollution in China (e.g., Chan and Yao, 2008; R. Zhang et al., 2013; Huang, 2018). In addition, multi-scale meteorological factors could modulate the formation, transportation, deposition, and chemical reactions of pollutants (Miao et al., 2015, 2016; Ye et al., 2016; Jiang et al., 2007; Zhang et al., 2012; Guo et al., 2013). During an annual cycle, most regions of China is influenced by the seasonal variations of East Asian monsoon, which could impact the seasonal variation of aerosol pollution in China (Zhang et al., 2010; Liu et al., 2011; Wang et al., 2014; Li et al., 2016; Wu et al., 2016). During a specific season, the variations of local meteorological conditions also modulate the pollution levels (Miao and Liu, 2017; Zhang et al., 2015a,b; Miao et al., 2018c). It is found that the heavy aerosol pollution in most regions of China are associated with weak wind, moist air mass, low boundary layer height (BLH), and strong low-level atmospheric temperature inversion (TI) (Wang et al., 2013; Li et al., 2015, 2017; Guo et al., 2016b; Miao et al., 2018b). Among these meteorological factors, the BLH may be one of

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the most important factors since it directly determine the total dispersion volume of pollutants (Hu et al., 2014; Tang et al., 2016; Miao et al., 2017b). During heavy pollution episodes, the low BLHs are often accompanied with strong TIs in the lower atmosphere, which could restrict the dispersion and mixing of pollutants emitted from surface (Malek et al., 2006; Wallace et al., 2010; Li et al., 2015; Miao et al., 2018c).

Wuhan, the most populous city of central China, lies in the eastern Jianghan Plain on the middle reaches of the Yangtze River (Fig. 1a). It is also one of most polluted cities in central China (Zhang and Cao, 2015). Partly due to the lack of appropriate observations, the relationships between planetary boundary layer (PBL) and aerosol pollution in Wuhan are rarely studied. Fortunately, in 2011, an L-band radiosonde system (Guo et al., 2016b; Zhang et al., 2018) was deployed in Wuhan (30.62 °N, 114.13 °E, Fig. 1a), which could provide fine-resolution profiles of temperature, pressure, humidity, and wind three times a day in summer (June-July-August) at 0800, 1400, and 2000 Beijing Time (BJT, i.e., UTC + 8h). Such radiosonde measurements provide us a unique opportunity to study the linkages between the PBL structure and aerosol pollution in Wuhan during summer, which constitutes one of the objectives in this study.

The development of PBL is not only controlled by local surface heat fluxes (Garratt, 1994), but also the external synoptic system (Miao et al., 2017b; Ye et al., 2016). Thus, in this study, we utilize a climatological approach (Miao et al., 2017b) to understand how these multi-scale factors impact the PBL structure in Wuhan during summer. The remainder of this paper is organized as follows. Section 2 describes the data and method used. In section 3, the associations between the aerosol pollution, PBL structure, and synoptic conditions are investigated. Finally, the key findings are summarized in section 4.

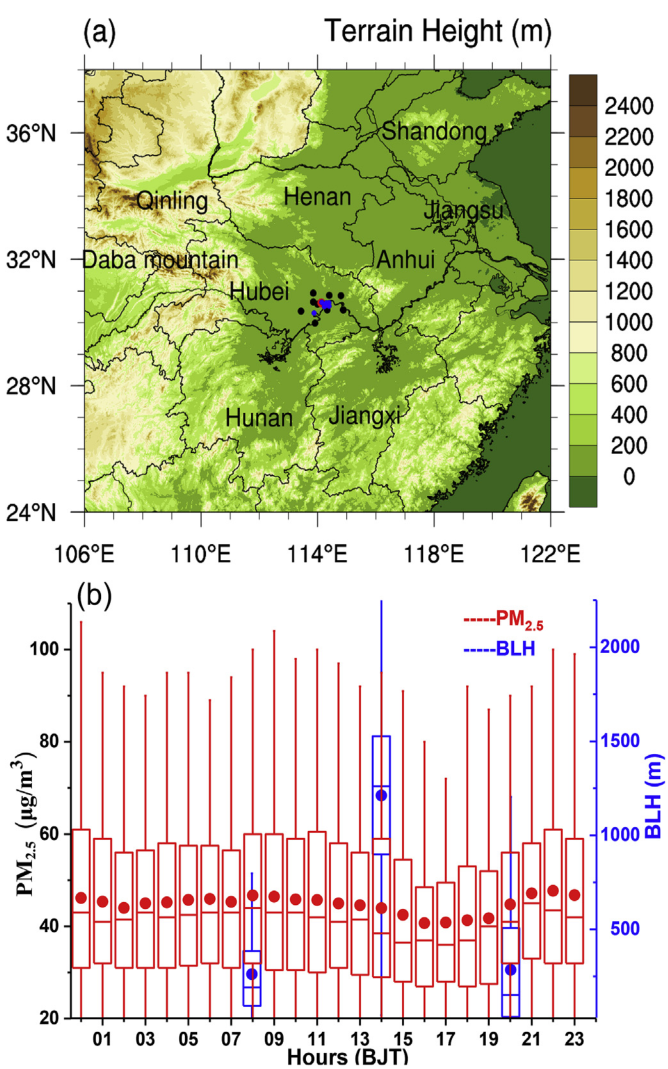

Fig. 1. (a) Spatial distribution of terrain height in central China, note that the sounding station (30.62°N, 114.13°E) in Wuhan is marked by the red dot, and the surface meteorological stations and air quality monitoring sites in Wuhan are denoted by the black dots and blue dots, respectively. (b) diurnal cycles of $PM_{2.5}$ concentration (in red) and boundary layer height (BLH, in blue) during summer in Wuhan. The central box represents the values from the lower to upper quartile (25th to 75th percentile); the vertical line extends from the 5th percentile to the 95th percentile; the middle solid line represents the median, and the dot represents the mean value. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2. Data and methods

2.1. Data

Here the summertime aerosol pollution level in Wuhan is denoted by near-surface $PM_{2.5}$ concentrations obtained from 10 air quality monitoring stations (Fig. 1a and Table S1) for the period 2013 to 2016. At each monitoring site, the hourly mass concentrations of $PM_{2.5}$ are measured using the micro oscillating balance method and/or β absorption method (Zhang and Cao, 2015). These 10 monitoring stations are well distributed in the urban areas, which can represent the $PM_{2.5}$ pollution level in Wuhan.

To understand the relationships between PBL and aerosol pollution in Wuhan during summer (June-July-August), the summertime radiosonde measurements collected from the Wuhan site (30.62 °N, 114.13 °E) for the period 2013 to 2016 were analyzed and compared with the near-surface $PM_{2.5}$ concentration. The Wuhan site, equipped with the L-band radiosonde system, provides PBL observations with fine-resolution three times a day during summer at 0800, 1400, and 2000 BJT. Besides, surface-level meteorological observations were also collected from 10 meteorological stations in Wuhan (Fig. 1a and Table S2) during the study period to understand the controlling factors of PBL structure, including 2-m temperature, 2-m relative humidity (RH), 10-m wind, and total cloud cover (CLD). Except the CLD are observed four times a day (0200, 0800, 1400, 2000 BJT), the other surface meteorological parameters are on hour-basis.

In addition to these observational data, the daily 925-hPa geopotential height (GH) fields derived from the National Center for Environmental Prediction (NCEP) global Final (FNL) reanalysis (https://rda.ucar.edu/datasets/ds083.2/) were analyzed to understand the relationships between large-scale synoptic patterns, PBL and pollution in Wuhan. The NCEP-FNL reanalysis fields are on $1^\circ \times 1^\circ$ grids with a 6-h temporal resolution at 0000, 0600, 1200 and 1800 UTC.

2.2. BLH and temperature inversions derived from soundings

In this study, we applied the bulk Richardson number (Ri) method to estimate the BLH from the high-resolution radiosonde measurements described in section 2.1. The Ri method has been proved to be a robust method to calculate the BLH both stable and convective boundary layers (e.g., Vogelezang and Holtslag, 1996; Seidel et al., 2012; Guo et al., 2016b). The Ri is defined as the ratio of turbulence associated with buoyancy to the turbulence caused by mechanical shear, which shows as below: