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Tethered balloon-based black carbon profiles within the lower troposphere of Shanghai in the 2013 East China smog

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HIGHLIGHTS

- A Tethered balloon-based black carbon measurement was firstly conducted in a megacity of China.
- Diurnal characteristics, formation, and sources of black carbon profiles were revealed.
- High atmospheric heating effects due to black carbon may influence regional climate.

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ABSTRACT

A Tethered balloon-based field campaign was launched for the vertical observation of air pollutants within the lower troposphere of 1000 m for the first time over a Chinese megacity, Shanghai in December of 2013. A custom-designed instrumentation platform for tethered balloon observation and ground-based observation synchronously operated for the measurement of same meteorological parameters and typical air pollutants. One episodic event (December 13) was selected with specific focus on particulate black carbon, a short-lived climate forcer with strong warming effect. Diurnal variation of the mixing layer height showed very shallow boundary of less than 300 m in early morning and night due to nocturnal inversion while extended boundary of more than 1000 m from noon to afternoon. Wind profiles showed relatively stagnant synoptic condition in the morning, frequent shifts between upward and downward motion at noon and in the afternoon, and dominant downward motion with sea breeze in the evening. Characteristics of black carbon vertical profiles during four different periods of a day were analyzed and compared. In the morning, surface BC concentration averaged as high as 20 $\mu g/m^3$ due to intense traffic emissions from the morning rush hours and unfavorable meteorological conditions. A strong gradient of BC concentrations with altitude was observed from the ground to the top of boundary layer at around 250–370 m. BC gradients turned much smaller above the boundary layer. BC profiles measured during noon and afternoon were the least dependent on heights. The largely extended boundary layer with strong vertical convection was responsible for a well mixing of BC particles in the whole measured column. BC profiles were similar between the early-evening and late-evening phases. The lower troposphere was divided into two stratified air layers with contrasted BC vertical distributions. Profiles at night showed strong gradients from the relatively high surface concentrations to low concentrations near the top of the boundary layer around 200 m. Above the boundary layer, BC increased with altitudes and reached a maximum at the top of 1000 m. Prevailing sea breeze within the boundary layer was mainly responsible for the quick cleanup of BC in the lower altitudes. In contrast, continental outflow via regional transport was the major cause of the enhanced BC aloft. This study provides a first

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insight of the black carbon vertical profiles over Eastern China, which will have significant implications for narrowing the gaps between the source emissions and observations as well as improving estimations of BC radiative forcing and regional climate.

1. Introduction

Owing to the strong economic development for the last few decades, China has been suffering from serious air pollution problems (Chan and Yao, 2008; Hao et al., 2007; Ouyang, 2013). The significance of trans-boundary transport of pollutants from East Asia, especially China has been extensively reported (Hand, 2014; Park et al., 2004; Yamazaki et al., 2014). For instance, it was reported that one O_3 pollution episode that occurred in Central California during 2012 was ascribed to be related to the long-range transport from China (Hand, 2014). Domestically in China, there have been urgent needs to mitigate air pollution, for it has become a big concern in economics (Lin et al., 2014), agriculture (Liu et al., 2013; Tai et al., 2014), transportation, public health (D'Amato et al., 2013; Kan et al., 2012; Tagaris et al., 2009), and climate change (Jacob and Winner, 2009).

In this regard, the Chinese government has made concerted efforts to tackle air pollution problems in recent years. For example, more rigorous national standard of air quality was promulgated and enforced in August 2013. Shortly after that, the State Council of China issued the Air Pollution Prevention and Control Action Plan. In April 2014, the environmental law was amended for better addressing the current status of air quality in China. Meanwhile, a comprehensive ground-based ambient air quality network for monitoring gaseous pollutants and particulate matters has been established in around 200 cities of the whole country so as to gain a better representation of the levels and spatial patterns of regional air pollution.

Two notorious large scale smog events hovered over North China in early January of 2013 and over East China in December of the same year (Wang et al., 2014; Xu et al., 2013). During these extreme air pollution events, hourly $PM_{2.5}$ concentration on Jan 12 recorded more than 900 $\mu g/m^3$ in Beijing; and the peak hourly $PM_{2.5}$ concentration on December 6 reached 602 $\mu g/m^3$ in Shanghai, 7–8 times higher than the national 24-h standard of 75 $\mu g/m^3$. High emissions, rapid formation of secondary aerosols and strong regional transport under the stagnant weather condition were investigated to be the major factors for the formation of these extreme haze events (Ji et al., 2014). However, most of the previous studies mainly focused on the characteristics of air pollutants on the surface level. Little has been known on the vertical variation of air pollutants in the lower troposphere; How would the variation of atmospheric boundary layer control the vertical mixing extent; And what's the impact of regional transport on the perturbation of air pollutants' vertical distributions.

Currently, the most widely applied instrumentations in the field measurement of vertical observation for airborne pollutants include aircraft, kite, tower, and the Tethered balloon platform. For aircraft based measurement, it was mainly focused on the mid- and high-altitudes of around 1–10 km (Ding et al., 2009; Yerramilli et al., 2008), but the vertical resolution is relatively low. Aircraft was used to carry on canisters sampling for the volatile organic compounds (Winkler et al., 2002). For a kite, it can be operated at a height as low as 100 m (Knapp et al., 1998), but the light-weight payload is the shortcoming for this platform. As for a tower, it is set up at a fixed site and also has limited observation range depending on the height of the tower. For example, in Beijing, there is a 325 m tower deployed for the measurement of meteorological and air pollutants fields (Meng et al., 2008). The well-known Eiffel tower in Paris was also used to collect observation data (Dupont et al., 1999). Measurements on the Frohnau Tower in Berlin were conducted to explore the cause of elevated PAN and O_3 (Rappengluck et al., 2004). As for a Tethered balloon, in theory it can be launched at any locations even in the harsh environment such as the South pole (Johnson et al., 2008) as well as in cities (Greenberg et al., 2009; Lin et al., 2007; Ma et al., 2013; Day et al., 2010; Cuchiara et al., 2014). Its application could be traced back to 1990's (Baumbach et al., 1993). However, the traditional Tethered balloon platform was also limited with the payload and generally could only carry the light-weight instruments.

In this study, we used a Tethered balloon to investigate the atmospheric chemistry in the lower troposphere, especially within the atmospheric boundary layer, in a metropolitan Chinese city, Shanghai. A custom-designed Tethered balloon filled with 1600 m^3 Helium with the payload capacity of 200 kg was used. This study is believed to be the first vertical airborne observation within the 1000 m troposphere over a metropolitan area in China. Particulate black carbon (BC) is the primary aerosol species investigated in this study. Although it only accounted for 5–10% of the aerosol mass in cities of China (Ni et al., 2012; Zhang et al., 2012), BC plays a significant role in the visibility degradation (Zhang et al., 2012), adverse health effect (Smith et al., 2009), and regional climate warming (Ramanathan and Carmichael, 2008). Its predominant sources are combustion related, e.g. fossil fuels consumption from transportation, industries, and residential usage, and open burning of biomass. Since BC is a relatively inert species, it could be regarded as a good tracer to probe the potential emission source region and the transport behavior of plumes at a specific receptor site. Most of the studies on the vertical distribution of black carbon focused on the altitudes of ~10 km with the vertical resolution of 0.5–1.0 km using aircrafts to explore the climate effect induced by BC (Babu et al., 2011; Rahul et al., 2014; Ramana et al., 2010; Xue et al., 2010). In Shanghai, very few studies on the vertical distribution of air pollutants were conducted. Geng et al. (2009) explored the vertical distribution of SO_2, O_3, VOC and NOx within 15 km in late-September and early-October over the Yangtze River Delta by means of an aircraft and suggested future traffic emissions will be responsible for the enhancement of O_3 pollution.

As a pilot study of the vertical observation of BC, we aim to explore the characteristics of BC profiles within the 1000 m lower troposphere over a Chinese megacity. BC profiles sampled during different time frames in a day were compared. The impact of varying meteorological conditions and boundary layer on shaping the BC vertical profiles was specifically assessed. The field experiment conducted in this study not only advances the atmospheric observational technology above the ground level, but also shed light on the nature and causes of heavy air pollution in China. It may also improve the performance and forecast accuracy of air quality models at the regional scale.