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Impact of meteorological conditions on a nine-day particulate matter pollution event observed in December 2013, Shanghai, China

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ABSTRACT

A severe particulate matter pollution event occurred in Shanghai from 1 to 9 December 2013. The mean hourly mass concentrations of $PM_{2.5}$ and PM_{10} were 211.9 and 249.0 $\mu g/m^3$, respectively. Reanalysis data, in situ, and remote-sensing measurements were used to examine the impacts of meteorological conditions on this event. It was found that the synoptic pattern of weak pressure, the reduced planetary boundary layer height, and the passage of two cold fronts were key factors causing the event. Four stages were identified during this event based on the evolution of its $PM_{2.5}$ levels and weather conditions. The highest concentration of $PM_{2.5}$ (602 $\mu g/m^3$) was observed in stage 3. High $PM_{2.5}$ concentrations were closely associated with a low local ventilation index, with an average of 505 m^2/s, as well as with the influx of pollutants from upstream, transported by the cold fronts.

Introduction

The rapid growth of megacities has led to serious urban air pollution in China (Chan & Yao, 2008; Mu & Zhang, 2014; Tie & Cao, 2009; Tie et al., 2006). Such severe air pollution is of great concern to the public and to local governments. According to the new national ambient air quality standards, GB 3095-2012, $PM_{2.5}$ has become the most important pollutant in many cities, especially megacities in China. Like other cities in Eastern China, Shanghai is experiencing more serious and more frequent air pollution events (e.g., haze) with high concentrations of $PM_{2.5}$ and low visibility (Chen et al., 2009; Fu et al., 2010; Wu et al., 2005). High concentrations of $PM_{2.5}$ may have important impacts on human health, climate change, and local ecosystems (Chen et al., 2013; Kan & Chen, 2003; Tie, Wu, & Brasseura, 2009; Xu, Li, Shi, He, & Pan, 2011). However, the processes causing heavy air pollution events in Shanghai are not well understood. Thus, it is necessary to examine the driving factors causing such severe air pollution events, especially for those with extremely high concentrations of $PM_{2.5}$.

Synoptic patterns are critical to air pollution events. Thus, their characteristics, emission sources, and meteorological contexts of air pollution events have been examined in Eastern China (Wang, Li et al., 2014; Wang, Yao et al., 2014; Zhang, Li, & Zhang, 2014). Anthropogenic emissions and meteorological conditions are the two most important factors causing poor air quality events (Fast et al., 2007; Jones, Harrison, & Baker, 2010). Given that little change in anthropogenic emissions occur over a short period (e.g., 1 month), meteorological conditions must play a dominant role in air pollution events. In addition to the weather conditions associated with high-pressure systems, other conditions, including warm weather before a cold front (WPBCF) or subsidence associated with a tropical cyclone (SPCTC), may cause air pollution events (Xu et al., 2011b; Wu et al., 2013). Zhang et al. (2014) examined meteorological conditions in January 2013 and showed that a weak winter monsoon and significant inversion in the low troposphere were favorable to the accumulation of particulate matter in cities.

Local meteorological conditions determine the build-up of air pollutants in cities (Elminir, 2005). Xu et al. (2011b) investigated the correlation between gaseous pollutants and meteorological conditions at a suburban North China Plain (NCP) site by using the HaChi (Haze in China) field campaign measurements and found that trace gas concentrations show a strong dependence on surface winds. Quan et al. (2013) examined the evolution of the planetary boundary layer (PBL) structure in Tianjing based on the measurements from the Micro Pulse Lidar (MPL) system and found an anti-correlated relationship between aerosol mass concentrations

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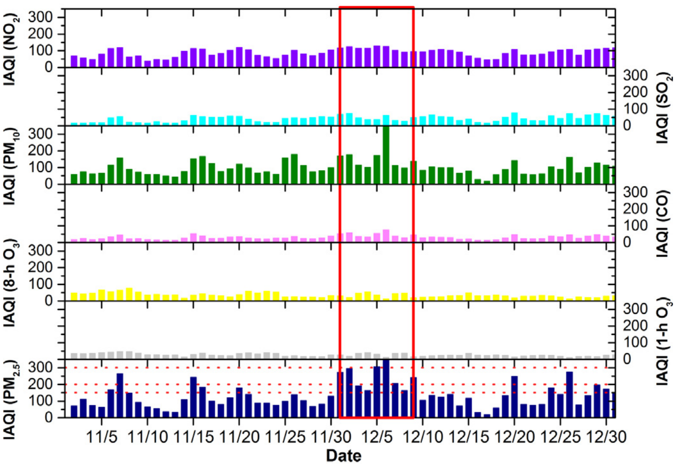

Fig. 1. Individual air quality index (IAQI) for NO_2, SO_2, CO, daily maximum 1-h ozone (1-h O_3), daily maximum 8-h ozone (8-h O_3), as well as $PM_{2.5}$ and PM_{10} from November to December 2013 for Shanghai (data from Shanghai Environmental Monitoring Center). The red rectangle denotes the severe pollution event from 1 to 9 December. The red dashed lines denote "unhealthy for sensitive people", "very unhealthy", and "hazardous" pollution level from lowest to highest, respectively.

and PBL heights. They proposed a positive link between PBL height reduction and surface aerosol enhancement. Tie et al. (2013) summarized the synoptic patterns that were conducive to high ozone events in Shanghai based on data from the MIRAGE (megacities impact on regional and global environment)-Shanghai campaign. However, meteorological conditions for extremely high $PM_{2.5}$ events in the Shanghai region have not yet been quantified.

A 9-day episode with extremely high $PM_{2.5}$ concentrations occurred in Shanghai from 1 to 9 December 2013. All available data, including reanalysis data, in situ, and remote sensing measurements, were used to examine the impacts of local meteorological conditions on this event and to identify the synoptic patterns that accounted for this event. In addition, these data were used to classify and characterize its different development stages.

Methods

Particulate matter episode, December 2013

Fig. 1 shows the individual air quality index (IAQI) of nitrogen dioxide (NO_2), sulfate dioxide (SO_2), carbon dioxide (CO_2), daily maximum 1-h and daily maximum (8-h) surface ozone (O_3), $PM_{2.5}$, and PM_{10} levels from November to December 2013. In China, ambient air quality indices are divided into six health impact categories, following regulations from the Ministry of Environmental Protection: "good" ($0 \le AQI \le 50$), "moderate" ($51 \le AQI \le 100$), "unhealthy" ($101 \le AQI \le 150$), "unhealthy for sensitive group" ($151 \le AQI \le 200$), "very unhealthy" ($201 \le AQI \le 300$), and "hazardous" ($AQI > 300$). The episode from 1 to 9 December 2013 included three "unhealthy for sensitive group" pollution days (i.e., December 3, 4, 8), four "very unhealthy" pollution days (i.e., December 1, 2, 7, 9), and two "hazardous" pollution days (i.e., December 5, 6). This was the first record of a continuous 9-day PM pollution event in Shanghai since the National Ambient Air Quality Standards (NAAQS, GB 3095-2012) were issued. During this event, the mean hourly mass concentration for $PM_{2.5}$ was 211.9 $\mu g/m^3$, while maximum hourly mass concentration reached 602 $\mu g/m^3$.

In situ measurements

Since 2011, Shanghai Environmental Monitoring Center has monitored trace gases (i.e., O_3, NO, NO_2, CO, SO_2) and particulate matter (PM_{10}, $PM_{2.5}$) throughout Shanghai. Its monitoring network includes 10 national environmental surface stations. Hourly mean values of these air pollutants were used to calculate AQI in accordance with regulations from the Ministry of Environmental Protection (China). In addition, hourly surface meteorological measurements (e.g., temperature, relative humidity, surface wind direction, and speed) are available from the Shanghai Baoshan Climate Observatory, a representative site of Shanghai in World Meteorological Organization (WMO). Finally, total cloud fraction was measured manually every hour at Shanghai Hongqiao International Airport Station. Data covering the period from 30 November to 10 December 2013 were used to characterize meteorological conditions and their impacts on ambient levels of $PM_{2.5}$ during the PM episode. Furthermore, near-surface wind data from December 2013 were compared with those during the December period from 2001 to 2012 to provide a long-term context to this air pollution event.

Remote-sensing data

We used measurements from a radar wind profiler (RWP) and MPL to calculate the ventilation index (VI) and characterize the PBL structure. Since 2007, a Vaisala LAP-3000 (Vaisala, Finland), wind profiler operated by the Shanghai Meteorological Bureau has been located in the Shanghai Pudong district (31.37°N, 121.53°E). This Doppler beam swinging RWP provides continuous profiles of horizontal wind speed and direction, and vertical velocity up to 3 km above ground level (AGL). The RWP is configured to cycle in "low" and "high" operational modes to optimize data completeness and resolution. In "low" operational mode, the RWP measured winds between 164 and 1537 m AGL at 23 levels (164, 226, 288, 351, 413, 476, 538, 601, 663, 726, 788, 850, 913, 975, 1038, 1100, 1163, 1225, 1287, 1350, 1412, 1475, and 1537 m). In "high" operational mode, the RWP measurements ranged from 1224 to 3538 m AGL at 25 different levels. In this study, only the "low" operational mode wind data were used to calculate VI, since these levels are within the PBL.

The MPL system was also set up in 2007. It was installed 20 m AGL within a cabin on a building roof. The bin time of the MPL receiver is set at 200 ns, corresponding to a 30-m vertical resolution. The MPL pulse repetition rate is about 2500 Hz. The blind zone after pulse correction is approximately 130 m. The PBL height was derived from these Lidar measurements using the algorithm proposed by He, Li, Mao, Lau, and Chu (2008); PBL height is defined at the place where the first significant negative gradient is observed. More detailed information about the MPL system can be found in He et al. (2012).

Reanalysis data

Monthly means from NCEP/NCAR Reanalysis (R1) products (Kalnay et al., 1996) provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA (Levitus & Boyer, 1998) were used to define meteorological conditions in December 2013. These variables were compared with the average climatology for December periods from 2001 to 2012. We included sea level pressure, geopotential height, temperature, U and V winds, relative humidity for 17-pressure levels on 2.5×2.5 degree grids.

NCEP FNL (Final) Operational Global Analysis data were used to describe daily synoptic evolutions between 30 November to 10 December 2013. This product is from the Global Data Assimilation System, which continuously collects observational data