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Scanning vertical distributions of typical aerosols along the Yangtze River using elastic lidar

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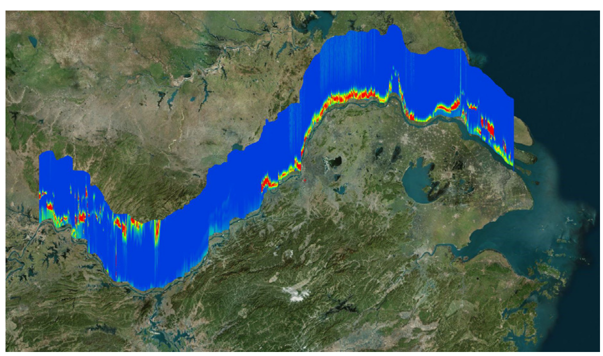
HIGHLIGHTS

- Dust aerosols were found to long range transport at relatively high altitudes to YRD regions in December.
- Dust was mixed with anthropogenic pollutants during transport.
- Biomass-burning aerosols covered a distant range along the Yangtze River.
- Some direct emissions and a probable secondary aerosol plume were observed.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent years, China has experienced heavy air pollution, especially haze caused by particulate matter (PM). The compositions, horizontal distributions, transport, and chemical formation mechanisms of PM and its precursors have been widely investigated in China based on near-ground measurements. However, the understanding of the distributions and physical and chemical processes of PM in the vertical direction remains limited. In this study, an elastic lidar was employed to investigate the vertical profiles of aerosols along the Yangtze River during the Yangtze River Campaign of winter 2015. Some typical aerosols were identified and some events were analyzed in three cases. Dust aerosols can be transported from the Gobi Desert to the Yangtze River basin across a long distance at both low and high altitudes in early December. The transport route was perpendicular to the ship track, suggesting that the dust aerosols may have affected a large area. Moreover, during transport, some dust was also affected by the areas below its transport route since some anthropogenic pollutants were mixed with the dust and changed some of its optical properties. Biomass-burning aerosols covering a distant range along the Yangtze River were identified. This result directly shows the impact areas of biomass-burning aerosols in some agricultural fields. Some directly emitted aerosol plumes were observed, and direct effects of such plumes were limited

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both temporally and spatially. In addition, an aerosol plume with very low linear depolarization ratios, probably formed through secondary processes, was also observed. These results can help us better understand aerosols in large spatial scales in China and can be useful to regional haze studies.

1. Introduction

China has recently suffered from severe air pollution characterized mostly by high concentrations of particulate matter (PM). Such pollution is inherently caused by the emissions of PM and gaseous pollutants (e.g., SO_2, NOx, and volatile organic compounds). Emissions are mostly concentrated in megacity clusters, such as the Beijing, Tianjin, and Hebei (BTH) region, the Pearl River Delta region, and the Yangtze River Delta (YRD) region (Zhao et al., 2013). However, few studies have focused directly on the areas between the cities comprising a cluster, let alone the areas outside those megacity clusters. Since regional haze has attracted increasing research attention (e.g. Wang et al., 2014; Zhao et al., 2013), and some important aerosol sources are outside of cities (e.g. Zhang and Cao, 2015), characterization of the aerosols at larger scales is important. Such a task can only be achieved using models and remote sensing. Atmospheric chemical transport models can be used to investigate the regional transport of pollutants. For example, Wang et al. (2014) used the Nested Air Quality Prediction Model System (NAQPMS) to investigate the spatial and temporal variations of $PM_{2.5}$ (PM with an aerodynamic diameter of ≤2.5 μm) in January 2013 over mid-eastern China. Their study showed that transport among cities within BTH and in cross-city clusters outside BTH contributed to 26%–35% and 20%–35% of $PM_{2.5}$, respectively, compared with the local emissions in BTH. In remote sensing, satellites can be used to directly characterize regional haze. After such an investigation, Tao et al. (2012) concluded that local- and regional-scale haze pollution in the North China Plain has different formation mechanisms. Remote sensing also can be used to investigate the long-term trends of some aerosol properties in a large spatial range. For example, Zhang et al. (2015) used satellite products to investigate the long-term spatiotemporal variations of haze over China. Light detection and ranging (lidar) is also a powerful optical remote measurement tool, and it is active range-resolved. Many aerosol studies have adopted such equipment. However, as a remote sensing technique, its typical usage cannot satisfy the need to characterize aerosols at a regional scale, because there is only one fixed measurement point in most cases. To compensate for this limit, one can load a lidar to a mobile platform such as an aircraft so that the lidar can keep moving. Many studies have used airborne lidar to draw spatial variations of aerosols around the world (McCormick, 2005), but there are no such studies specifically in China. Moreover, only a few studies have adopted lidar aboard a motor vehicle that moved over a city scale (e.g. Lv et al., 2016).

In terms of lidar itself, it obtains vertical profile information for the atmosphere, such as vertical distributions of aerosols and ozone. These data are largely optical information, but they also contain some other types of information. The most important optical processes involved in aerosol lidar measurements are absorption and scattering of light by aerosol particles. Many aerosol properties would affect such processes, leading these properties to be captured by the light. Among such properties, the most common one is the aerosol extinction coefficient, which can reflect PM concentrations. Other properties, such as aerosol microphysical parameters (Muller et al., 1999; Wang et al., 2012) and depolarization properties, can also be extracted. All such properties could be used to identify aerosol types and sources. For example, depolarization is generated by non-spherical particles (Sassen, 2000). Since dust aerosols are generally composed of non-spherical particles, many studies have identified dust aerosols using the depolarization ratio (Gross et al., 2011; Liu et al., 2013; Pan et al., 2015; Shimizu et al., 2004; Sugimoto et al., 2003; Yu et al., 2015). In recent years, the depolarization ratio has also been used, along with other properties such as the lidar ratio and the backscatter color ratio, to identify other types of aerosols (Burton et al., 2012). In the work conducted by de Foy et al. (2011), different aerosol plumes, including biomass burning, dust, and urban aerosols were identified using high-spectral-resolution lidar aboard an aircraft.

In this study, we loaded a dual-wavelength elastic polarization lidar onto a ship sailing from Shanghai to Wuhan, during the Yangtze River Campaign (YRC) of winter 2015. The primary objective of this study was to investigate the spatial distributions of aerosols along the Yangtze River, especially the vertical distributions. Typical types of aerosols were also analyzed based on the retrieved vertical profiles of aerosol optical properties, including extinction coefficient and linear depolarization ratio (LDR). The YRD, in which Shanghai is located, is one of the most developed regions in China, experiencing substantial increases in wintertime haze during the past decades. Wuhan is a megacity of Central China suffering from severe PM pollution. The region from YRD to Wuhan is also rapidly developing, and as such our study is of special interest.

2. Materials and methods

2.1. Yangtze River campaign

On November 21, 2015, a ship loaded with various scientific instruments set out from Shanghai and traveled along the Yangtze River. The ship arrived at Wuhan (30.62°N, 114.33°E), the capital of Hubei Province, China at 15:42, November 29, and instantly turned around and returned to Shanghai on December 4 (end of campaign). The ship track is shown in Fig. 1. A dual-wavelength elastic polarization lidar was used to scan the optical properties of the atmospheric particles during its travel. Instruments belonging to the *i* series from Thermo Fisher Scientific, Inc. were used to provide the online data for NO*x* (42i), SO_2 (43i), and CO (48i). A SIDEPAK AM510 from TSI was used to measure online $PM_{2.5}$, and a Biral Visibility & Present Weather Sensor was used to measure visibility.

2.2. Lidar observations

The elastic polarization lidar (AGHJ-1-LIDAR) used in this study was developed by the Anhui Institute of Optics and Fine Mechanics (AIOFM). This shipboard lidar is similar to the instrument used on board a motor vehicle by Lv et al. (2016). The laser source was a pulsed Nd:YAG solid laser (Quantel Ultra 100) emitting short pules at 532 and 355 nm. The typical pulse energy of the laser was about 20 mJ, the pulse repetition rate was 20 Hz, and the pulse duration was approximately 9 ns. The laser beam was emitted with a divergence of 0.25 mrad. Beam direction was controlled by x–y mounts to align the laser beams within the field of view of the telescopes, and the beams were emitted vertically into the atmosphere. The beam splitters, which were optimized for different wavelengths, operated at a 45° angle of incidence. Their coatings worked for both parallel and perpendicular polarizations. The light then passed through a combination of broadband and narrowband interference filters, and neutral density filters. These combinations were used to adapt the light intensity of the signals to the sensitivity of the corresponding detectors. The system had high out-of-band rejection ratios (10^{-6}–10^{-7}). The receiving telescope of the system was based on a Cassegrain telescope with a diameter of 158 mm off-axis to the receiving telescope with a field of view (FOV) of 0.5 mrad, resulting in an overlap height of <200 m. Transient recorders were used to digitize the