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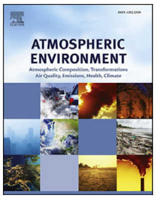

Continuous ground-based aerosol Lidar observation during seasonal pollution events at Wuxi, China

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HIGHLIGHTS

- Two pollution events are characterized at Wuxi, China from 2013 to 2014.
- Lidar-derived extinction coefficient and depolarization ratio integrated with air quality and meteorological data are analyzed.
- Causes of these episodes are seasonally-based: winter haze conceptualizes compound pollution, $PM_{2.5}$ and O_3 are main pollutants in summer.

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ABSTRACT

Haze pollution has long been a significant research topic and challenge in China, with adverse effects on air quality, agricultural production, as well as human health. In coupling with ground-based Lidar measurements, air quality observation, meteorological data, and backward trajectories model, two typical haze events at Wuxi, China are analyzed respectively, depicting summer and winter scenarios. Results indicate that the winter haze pollution is a compound pollution process mainly affected by calm winds that induce pollution accumulation near the surface. In the summer case, with the exception of influence from $PM_{2.5}$ concentrations, ozone is the main pollutant and regional transport is also a significant influencing factor. Both events are marked by enhanced $PM_{2.5}$ concentrations, driven by anthropogenic emissions of pollutants such as vehicle exhaust and factory fumes. Meteorological factors such as wind speed/direction and relative humidity are also contributed. These results indicate how the vertical profile offered by routine regional Lidar monitoring helps aid in understanding local variability and trends, which may be adapted for developing abatement strategies that improve air quality.

1. Introduction

Atmospheric aerosols are an important part of the earth-atmosphere-maritime system. They affect the climate through three primary components: (i) direct scattering or absorption on short-wave and long-wave radiation, namely direct radiative forcing; (ii) varying aerosol concentrations change the characteristics of clouds: perturbed numbers of aerosol particles acting as cloud condensation nuclei influence the number of the cloud particles per unit volume, which can also impact effective cloud droplet radii, cloud shortwave reflectance, and cloud lifetime, known as indirect radiative forcing; (iii) aerosols can also change various atmospheric chemical processes, affect the concentration and distribution of greenhouse gases, and thus impact climate (Kaufman et al., 1997). Aerosol radiation forcing remains a key factor driving current uncertainties relating to manifestations of climate change.

With the recent acceleration of industrialization and urbanization processes in China, rapid economic development and expansion has caused environmental problems to become more apparent. Continuous emissions of greenhouse gases enhance global warming through positive feedback, inducing long-term changes in each part of the climate system that will increase the

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possibility of serious, widespread and irreversible impact on human and ecological system. The growth and relevance of satellite and ground-based remote sensing observations of regional and urban aerosols in the most susceptible regions of China has led to a rapid characterization of chemical and physical aerosol properties there (e.g., Zhang et al., 2015, 2016; Qin et al., 2016), allowing for the research community to quickly devise strategies that help urban officials design strategies that mitigate hazardous conditions (Wong et al., 2015; Xiao et al., 2015).

Light Detection and Ranging (Lidar) is an effective and reliable method to monitor and profile geometric and optical properties of aerosols and clouds. Lidar instruments are predominantly used for profiling the structure of aerosol particles throughout the troposphere, either from ground (e.g., Campbell et al., 2002) or satellite (Spinhirne et al., 2005; Winker et al., 2010). Commercial and prototype Lidars are currently deployed in global federated network for aerosol and cloud measurement activities such as the Micro Pulse Lidar Network (MPLNET) (Welton et al., 2001), the European Aerosol Research Lidar Network (EARLINET, Matthias et al., 2004; Pappalardo et al., 2014), and the Asian Dust Network (ADNET, Murayama et al., 2001). Coupled with the sun photometers operated by the AErosol RObotic NETwork (AERONET), synergistic observations based on ground-based profiling and column-integrated optical property measurements have provided the community with an example paradigm for how routine monitoring and long-term climatological evaluation of aerosol properties is possible. Further, these observations provide critical ground verification for aerosol satellite-observing missions (e.g., Fromm et al., 2014).

Significant progress in the theory and application of Lidar aerosol detection has occurred in China. The Institute of Atmospheric Physics of Chinese Academy of Sciences developed the first atmospheric aerosol detection Lidar system in the mid-1960s. The Institute further developed a Mie-scattering backscatter instrument and large multi-wavelength Lidar for measuring aerosol extinction and atmospheric slant visibility (Zhang, 2007). In 1995, Anhui Institute of Optics and Fine Mechanics (AIOFM) developed a portable dual-wavelength (532 nm and 1064 nm) Mie-scattering Lidar, L300, which was used in the observation with aerosol extinction coefficient, depolarization ratio of dust and clouds, and horizontal visibility (Zhou et al., 1998). The Ocean University of China completed the first non-coherent Doppler wind Lidar system in China, featuring the high spectral resolution Lidar technique (HRSL) (Liu et al., 1996, 1997, 1999; Zhang, 2007).

In addition, the China Meteorological Administration began building the Chinese Aerosol Observation Network (CAeroNet) in 2002, establishing twenty observing stations mainly in the dust source regions to the north and west near the primary deserts. Chemical and particle aerosol air monitoring data, including SO_2, NO_x, CO, PM_{10} concentrations, have been collected in China since 2000. Other air quality parameters, such as $PM_{2.5}$, have been monitored in China since approximately 2012. The Chinese government released data from 367 stations in 2015. CAeroNet also uses CIMEL sun photometers (Model CE318-II) for atmospheric aerosol column-integrated monitoring (Yan et al., 2006). The Institute of Atmospheric Physics (IAP) at the Chinese Academy of Sciences (CAS) established the Chinese Sun Hazemeter Network (CSHNET) in August 2004 (Xin et al., 2007), based on the measurements of column-integrated aerosol optical thickness. These observations better describe the temporal and spatial distribution of atmospheric aerosol optical properties in China (Wang et al., 2007). However, due to the sparse geographical locations of these stations, as well as their ground-based observations, the vertical distribution, formation, sources and trends of aerosols are difficult to analyze.

This paper introduces continuous aerosol monitoring observations from Lidar at Wuxi, China (30°30′N, 120°21′E). Observations similar to that collected by MPLNET are made there with an autonomous Lidar-D-2000, developed by Wuxi CAS Photonics Co. Ltd. Observations began in 2012 and are collected in a relatively continuous manner. Here, we describe two case studies investigated using these data, combining measurement profiles of aerosol extinction estimated from the Lidar with backscatter depolarization measurements that help estimate those aerosol types present. These data are paired with a series of chemical and particle sampling measurements of surface-based aerosols as well as surface meteorology. We further analyze air mass backward trajectories so as to analyze the pollution trajectories and likely sources. Our goal is to conceptualize how Lidar measurements, and in particular continuous network-based Lidar profiling, can be adapted to in order to help better understand aerosol formation and transport mechanisms, as well as the physical and optical characteristics of regional aerosols, in China.

2. Data and methods

2.1. Ground-based Lidar

The Lidar-D-2000 is a dual-wavelength three-channel Mie scattering Lidar. The Lidar operates at two wavelengths (355 nm and 532 nm), with backscatter measured in three channels: 355 nm total, 532 nm parallel-polarized and 532 nm orthogonal. Thus, the 532 nm channels are polarized so as to detect and profile the morphological characteristics of particulate matter (e.g., Sassen, 1991; Song et al., 2012). The 355 nm channel, in contrast, is used for analysis of fine particulate matter and ratio measurements relative to the 532 nm channel that help resolve size characteristics. The detection range of Lidar-D-2000 can reach to 30 km, with a standard temporal resolution of 1 min, and standard range resolution of 7.5 m.

The Lidar backscatter equation is written as

$$P_r(r) = P_0 k r^{-2} \beta_T(r) \exp\left\{ -2 \int_0^{r'} \alpha_T(r') \mathrm{d}r' \right\} \tag{1}$$

Here, $P_r(r)$ is the atmospheric backscatter signal at height r, P_0 is the emitted Lidar energy, k is Lidar system constant, $\beta_T(r)$ is total atmospheric backscatter coefficient at 532 nm from both polarized channels, and $\alpha_T(r)$ is the range-integrated atmospheric extinction term. The ratio of $\alpha(r)$ and $\beta_T(r)$ is the so-called '*Lidar ratio*', or extinction-to-backscatter ratio, which represents a practical mean for converting measured backscatter to extinction, since the two unknown terms in (1) cannot be solved directly. The extinction coefficient is estimated using the 532 nm parallel channel (Dong et al., 2015). As Lidar-D-2000 is a Mie-backscatter Lidar, outputs for aerosol extinction here are unconstrained and thus estimates, meaning that we apply a static value of the extinction-to-backscatter ratio of 50 sr (assuming urban and mineral mixtures at 532 nm; e.g., Ackermann, 1998) to initiate the retrievals (e.g., Fernald, 1984). The data have not been cloud-cleared, with such elements referred to in the text to avoid confusion.

As a polarization Lidar, the Lidar-D-2000 receives two separate channels: the parallel (with respect to the emitted light) and the perpendicular light. The volume depolarization ratio is defined as the ratio of the total perpendicular to the total parallel-polarized backscatter coefficient at 532 nm channel. It should be noted that the calculations of depolarization ratio were based on relative measurements with assumption of single scattering condition, and no multiple scattering corrections have been applied to the data