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Assessment of satellite-based aerosol optical depth using continuous lidar observation

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HIGHLIGHTS

- 5-year continuous lidar measurements were used to assess the satellite-based AOD.
- Different seasonal variation in AOD is observed by MODIS and lidar over Hong Kong.
- Aerosols in the upper mixing layer largely increase AOD at midday during summer.
- Long-term average of AOD, estimated from satellite observation, may has large error.

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ABSTRACT

Due to a reliance on solar radiation, the aerosol optical depth (AOD) is observed only during the day by passive satellite-based instruments such as the MODerate resolution Imaging Spectroradiometer (MODIS). Research on urban air quality, atmospheric turbidity, and evolution of aerosols in the atmospheric boundary layer, however, requires 24-h measurement of aerosols. A lidar system is capable of detecting the vertical distribution of the aerosol extinction coefficient and calculating the AOD throughout the day, but routinely lidar observation is still quite limited and the results from MODIS and lidar sometimes are contradictory in China. In this study, long-term lidar observations from 2005 to 2009 over Hong Kong were analyzed with a focus on identification of the reasons for different seasonal variation in the AOD data obtained from MODIS and lidar. The lidar-retrieved AOD shows the lowest average level, but has the most significant diurnal variation during the summer. When considering only a 5-h period between 10:00 a.m. and 3:00 p.m. local time to match satellite passages, the average of the lidar-retrieved AOD doubles during the summer and exceeds that during the winter. This finding is consistent with the MODIS observation of a higher AOD during the summer and a lower AOD during the winter. The increase in the aerosol extinction coefficient in the upper level of the mixing layer makes the greatest contribution to the increase in the AOD at midday during the summer. These assessments suggest that large over-estimation may occur when long-term averages of AOD are estimated from passive satellite observations.

1. Introduction

Given the large spatiotemporal variabilities and complex physical and chemical properties of aerosols, estimates of their corresponding earth's radiative forcing patterns are still complex and

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highly-uncertain (Min et al., 2009; Satheesh and Krishna Moorthy, 2005). Reduction of these uncertainties requires routine observation of aerosol distributions and properties at high spatiotemporal resolutions (Groß et al., 2013). Satellite sensors routinely observe the aerosol optical depth (AOD), a column integral of light extinction coefficients of aerosols in the atmosphere, at high spatial coverages (Jerrett et al., 2004; Kaufman et al., 2002). Observations of the AOD from the MODerate resolution Imaging Spectroradiometer (MODIS) instruments aboard NASA's Earth observing system (EOS) polar-orbiting satellites, Terra and Aqua, have been extensively used to estimate the spatial distributions of aerosols (Chu et al., 2003; Li et al., 2003, 2015; Lin et al., 2015). Due to a reliance on solar radiation, AOD is observed only during the day from these passive instruments. Research on urban air quality, atmospheric turbidity, and evolution of aerosols in the atmospheric boundary layer, however, requires 24-h measurement of aerosols (Berkoff et al., 2011; Pérez-Ramírez et al., 2011). In addition, reliable aerosol measurements during nighttime would improve our understanding of the complete effect of aerosols in the climate feedback system (Johnson et al., 2013; Zhang et al., 2008). Unfortunately, ground-level measurement of the column-integrated values for AOD from the aerosol robotic network (AERONET) (Holben et al., 1998) is also restricted to during the day, and is thus unable to provide information on the evolution of aerosols in the atmospheric boundary layer. A few new sensors that take advantage of moonlight (Berkoff et al., 2011; Esposito et al., 1998) or starlight (Herber et al., 2002; Pérez-Ramírez et al., 2011) have been developed to measure AOD during nighttime. These sensors, however, are either limited by the inconsistent availability of the lunar source and non-Lambertian reflectance properties of the moon (Kieffer, 1997), or expense and complex to collect sufficient starlight (Berkoff et al., 2011), leading to the fact that lunar and stellar measurements are still limited in use (Berkoff et al., 2011). The measurement of nighttime AOD from space is in its infancy and deserves further evaluation, but nevertheless is a subject of ongoing interest (Johnson et al., 2013).

Lidar is an active remote sensing system that is capable of detecting the vertical distribution of the aerosol extinction coefficient and calculating the AOD throughout the day at high spatiotemporal resolution (Spinhirne, 1993). Long-term variation in the AOD and aerosol vertical distribution has been intensively investigated with the use of long-running lidar systems around the world. By analyzing observations from MODIS and lidar in eastern Asia, Kim et al. (2007) noted that seasonal variation in the AOD from the two data sets shared a similar feature, with a maximum in the spring when Asian dust storms frequently occur. On the basis of lidar measurements over M'Bour in Senegal from 2006 to 2008, Léon et al. (2009) observed a maximum of dust activity and AOD (above 0.5) during summer. Raman lidar observations from Greece from 2001 to 2004 showed an average AOD of about 0.63, of which free tropospheric particles accounted for about 30% (Amiridis et al., 2005). By analyzing 1-year of lidar measurements in India, Sinha et al. (2013) showed that aerosols within the atmospheric boundary layer and in the free troposphere contributed about 0.37 (77.7%) and 0.12 (22.3%), respectively, to the total AOD.

Therefore, lidar observation of the aerosol vertical distribution and AOD is valuable for the assessment of the long-term variation in the MODIS AOD. Although satellite-based lidar sensors are also able to observe aerosol vertical distribution during daytime and nighttime, the estimates are still suffer from coarse spatiotemporal resolution, signal attenuation, and large bias resulted from the assumed lidar ratio (Campbell et al., 2013). Long-term ground-based lidar observation, however, is still quite limited especially in China (Yang et al., 2013). Results from MODIS and lidar sometimes are contradictory. He et al. (2008) analyzed the characteristics of the seasonal averages of aerosol profiles and observed the lowest AOD during summer with the use of 24-h lidar measurements from May 2003 to June 2004 over Hong Kong. In contrast, a higher level of AOD was observed during summer than during winter by analysis of the MODIS observations (Li et al., 2003). It is therefore important to identify the reasons for the different seasonal variation in the AOD data from MODIS and the 24-h lidar observation.

In this study, long-term lidar observations from a 5-year period from 2005 to 2009 over Hong Kong were analyzed. The long-term running lidar provides crucial information for characterization of the long-term variation in the aerosol vertical distribution and AOD in this region. Diurnal, monthly, and seasonal variation in the aerosol vertical distribution and AOD were derived and analyzed with a focus on characterizing the different seasonal variation in AOD data from MODIS and the lidar. This paper is organized as follows. In the Data and Measurement section, the measurements from MODIS, lidar, a visibility sensor, and radiosondes are introduced. In the Results section, the diurnal, monthly, and seasonal variation in the aerosol vertical distribution and AOD from MODIS or the lidar are obtained and analyzed. Finally, the reasons for the different seasonal variation in the AOD data from MODIS and the lidar are further discussed.

2. Data and measurements

2.1. Lidar

2.1.1. Instrument

The micropulse lidar (MPL) system was installed at Yuen Long (114.02°E 22.44°N, as shown in Fig. 1), a residential town in the northwest of Hong Kong. Hong Kong is located in the southeast part of the Pearl River Delta (PRD) region, which is one of the most highly-populated and rapidly-developing regions in China (Cao et al., 2003). The weather in this region is influenced by the southerly or southwesterly East Asia monsoon during the summer and by the northerly or northeasterly monsoon during the winter (Yuan et al., 2013). Rapid urbanization and industrialization have caused heavy air pollution problems in this region (Li et al., 2015;

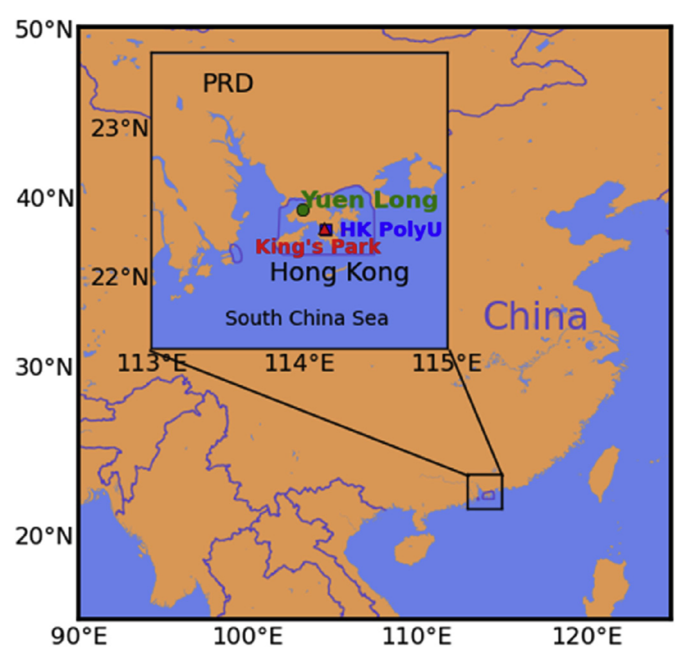

Fig. 1. Map of Hong Kong and the Pearl River Delta (PRD) in China.