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Characterization of vertical distribution and radiative forcing of ambient aerosol over the Yangtze River Delta during 2013–2015

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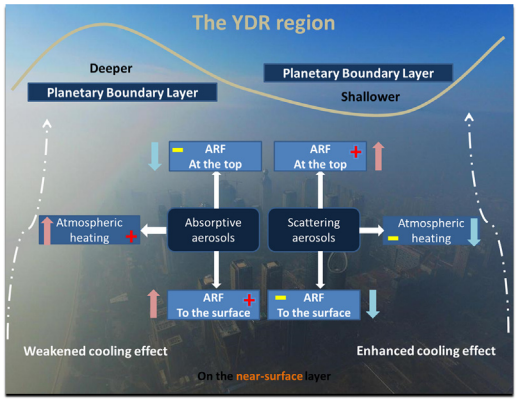
HIGHLIGHTS

- In YRD, scattering aerosols in June enhance the cooling effect and depress PBL.
- Near-surface absorptive aerosols weaken the cooling effect and lift PBL in August.
- Deeper PBL agrees to stronger ARF-BOA and atmospheric heating effects.

GRAPHICAL ABSTRACT



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ABSTRACT

As the central part of eastern China, the Yangtze River Delta (YRD) region, with its rapid economic growth and industrial expansion, has experienced severe air quality issues. In this study, the monthly variation and interaction between aerosol direct radiative forcing (ADRF) and aerosol vertical structure during 2013–2015 over the YRD were investigated using ground-based observations from a Micro Pulse Lidar (MPL) and a CE-318 sunphotometer. Combining satellite products from MODIS and CALIPSO, and reanalysis wind fields, an integrated discussion of a biomass burning episode in Hangzhou during August 2015 was conducted by applying analysis of optical properties, planetary boundary layer (PBL), spatial-temporal and vertical distributions, backward trajectories, Potential Source Contribution Function (PSCF), and Concentration Weighted Trajectory (CWT). The results reveal that a shallower PBL coincides with higher scattering extinction at low altitude, resulting in less heating to the atmosphere and radiative forcing to the surface, which in turn further depresses the PBL. In months

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Planetary boundary layer
Vertical structure

with a deeper PBL, the extinction coefficient decreases rapidly with altitude, showing stronger atmospheric heating effects and ADRF to the surface, facilitating the turbulence and vertical diffusion of aerosol particles, which further reduces the extinction and raises the PBL. Because of the hygroscopic growth facilitated by high relative humidity, June stands out for its high scattering extinction coefficient and relatively low PBL, and the reduced ADRF at the surface and the enhanced cooling effect on near-surface layer in turn depresses the PBL. Absorptive aerosols transported from biomass burning events located in Zhejiang, Jiangxi, and Taiwan provinces at 1.5 km, result in high ADRF efficiency for atmospheric heating. And the enhanced heating effect on near-surface layer caused by absorptive particles facilitates PBL development in August over the YRD.

1. Introduction

Solar irradiance is the most important energy for atmospheric movement and an external forcing factor that influences the weather and climate (Yang et al., 2010a). Aerosol direct radiative forcing (ADRF) refers to the scattering and absorption of solar radiation by atmospheric aerosols, which reduces the amount of solar radiation reaching the earth's surface and increases the solar heating of the atmosphere, thereby affecting the earth's temperature and climate variation (Ramanathan et al., 2001; Jacobson, 2001; Hansen et al., 1997; Che et al., 2014; Li et al., 2011). There have been researches on the effect of ADRF over multiple cities in China and their impact on the air pollution (Yang et al., 2016; X. Yang et al., 2017). And a wealth of studies on ADRF are conducted by remote sensing or model simulations (Haywood and Boucher, 2000; Chen et al., 2017; Zhang et al., 2017; Hong et al., 2017), particularly employing ground-based sun-photometers to retrieve aerosol optical properties and calculate ADRF (Dubovik et al., 2002; Kim et al., 2004; Che et al., 2014; Patel et al., 2017).

The planetary boundary layer (PBL) is directly coupled with the earth's surface and has a strong influence on tropospheric air pollution. In the PBL, rapid exchanges of heat, moisture, and chemical constituents take place between the free atmosphere and the surface. The PBL height (PBLH) is a key parameter in the simulation and forecast of air quality, not only from ground-based observation but also based on satellite measurement (Deardorff, 1972; Konor et al., 2007; Lin et al., 2008; Zheng et al., 2017). The PBLH is significantly influenced by the aerosol direct radiative effect, on the contrary, variation of PBLH interacts with aerosol dispersion and thereby ADRF. Yang et al. (2016) found that the contribution to improving atmospheric visibility from interactions between surface direct solar radiation and atmospheric visibility was estimated at approximately 15% in south Beijing during the APEC period. However, there is a complex interaction between the PBLH and ADRF (Stull, 1988; Garratt, 1994; Liu and Liang, 2010), and needs more intensive study on the mechanism of it.

China has experienced rapid economic growth by expanding industrialization, explosive growth in transportation, and intensive anthropogenic activities (Che et al., 2015; Sun et al., 2016), particularly in a few rapid-growing regions such as the Beijing-Tianjin-Hebei (BTH) region, the Pearl River Delta (PRD) region, the Yangtze River Delta (YRD) region and Hong Kong (Fig. 1), which leads to deterioration of air quality and impacts regional climate change (Luo et al., 2001; Zhang et al., 2013; Li et al., 2013; Yang et al., 2018; Tao et al., 2014).

As the central part of eastern China, the YRD region shows unique characteristics in geological locations and synoptic characteristics (Li et al., 2013; Shu et al., 2017; Qi et al., 2016; Chen et al., 2006), climatic conditions (Hu et al., 2016; Tao et al., 2016), loadings of particulate matter with a diameter <2.5 μm ($PM_{2.5}$) (Li et al., 2014; Ming et al., 2017), and aerosol optical properties (Li et al., 2015b; Sun et al., 2017). Much progress has been made on the aerosol optical properties and radiative properties, surface $PM_{2.5}$ concentrations, as well as vertical aerosol profile, PBLH. However, what they have focused on are their diurnal variations or case analysis of YRD region, but lack of specific long-term monthly analysis and corresponding comprehensive interpretation. Besides, as for the vertical structure, they are more about the effect of PBL's variation on aerosol distributions during one haze event, but ignore the possibility the influence of aerosol optical and radiative properties on the weather parameters and the variation of PBL. Generally, previous studies have not investigated the mechanisms behind the phenomenon

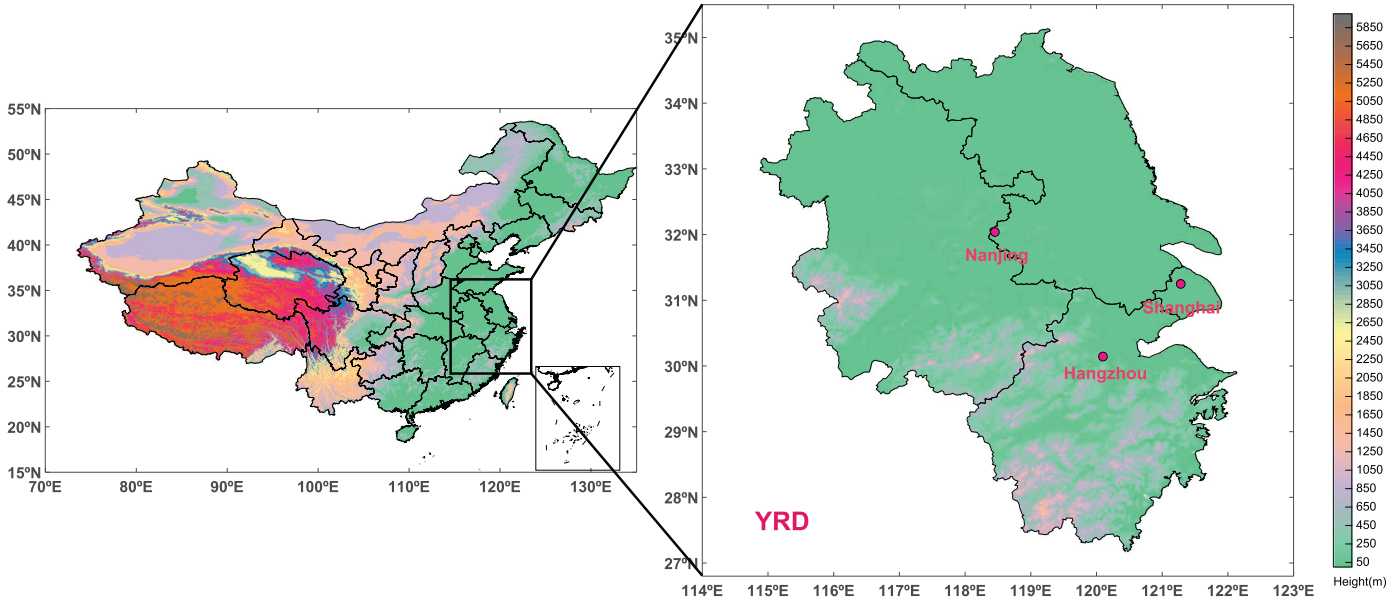

Fig. 1. Terrain elevation and location of the Yangtze River Delta region in China.