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Spatial–temporal characteristics of haze and vertical distribution of aerosols over the Yangtze River Delta of China

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ABSTRACT

Variation of haze events occurred in the Yangtze River Delta (YRD) of China, the characteristics of meteorological elements and the vertical distribution of aerosols during haze episodes were analyzed by utilizing data of ground observation, radiosonde and CALIPSO. The results illustrate that the frequency of haze events between 1981 and 2010 peaked in winter but bottomed out in summer and decreased from north to south in the YRD region, reaching at the lowest point in "low frequency center" — Shanghai. When haze happened, the most seriously affected area was 2–4 km above the ground and the concentrated range of total backscattering coefficient (TBC) that decreased with altitude was 0.8×10^{-3}–2.5×10^{-3} km^{-1}/sr. Particulate depolarization ratio (PDR) was less than 40% in a large part and 93% aerosols over the YRD area were regular particles, while the irregular ones concentrated on 2 km above the surface and the irregularity rose up but the diversity diminished when altitude increased. Color ratio (CR) was lower than 1.2 mostly at all altitudes and distributed asymmetrically above the ground. Nearly 80% aerosols under 10 km were fine particles (CR < 1.0) and 22.54% coarse particles (CR > 1.0) clustered at 2–4 km. Large particles (CR > 1.2) aggregated in lower troposphere massively yet relatively smaller ones gathered in middle and upper troposphere. In the YRD region, aerosols with more powerful capabilities were wider and less regular than the ones of Northwestern China.

Introduction

Haze is one of air pollution phenomena, which is defined as visibility lower than 10 km when relative humidity is below 80% without precipitation, dust storm, blowing sand, floating dusts, smoke, blowing snow and snow storms (China Meteorological Administration, 2010) and whose higher frequency of occurrence in recent years and pernicious effects on human body have raised public concern as well as the scientific community in China (Zhang et al., 2012, 2015).

The Yangtze River Delta (YRD) region that covers about 99,600 km^2 with a population of 150 million, located in the east coast of China and including 16 core cities (the Shanghai municipality, 7 cities in the north of Zhejiang Province and 8 cities in the south of Jiangsu Province), contributed 18.5% of the national GDP in 2014. However, due to its rapid economic

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development with dramatic increased in energy consumption and pollutant emissions in the last 30 years, regional air pollution problems have become more and more salient, such as deteriorated urban air quality and declined visibility, all of which have made the YRD, together with the Pearl River Delta, Beijing–Tianjin–Tangshan and Sichuan–Chongqing, become one of the four heaviest haze regions in China (Fu et al., 2008; Wang et al., 2012; Cheng et al., 2013, 2014).

Previous studies have revealed that unfavorable meteorological elements, *e.g.*, high relative humidity, low rainfall, wind speed, atmospheric pressure, and extremely high concentrations of aerosol particles, including fine particulate matter, played critical roles in the formation of haze in the YRD area (Fu et al., 2008; Cheng et al., 2013; Tian et al., 2016; M. Wang et al., 2015; W. Wang et al., 2015; Zhang et al., 2015). In addition, optical, microphysical properties, such as: size distribution, number concentration, and temporal–spatial distribution of aerosols during haze episodes were detected by ground-based field sampling measurements (Fu et al., 2008; Zhang et al., 2012, 2017; Cheng et al., 2013; Hu et al., 2014; Wang et al., 2014; M. Wang et al., 2015; W. Wang et al., 2015; Tian et al., 2016; Cui et al., 2016). Furthermore, numerical models were utilized to simulate the transport trajectory and forecast urban air quality in haze weather (Wang et al., 2012; Cheng et al., 2014), emission inventories of pollutants of the YRD region were also established (Huang et al., 2011; Fu et al., 2013). However, due to limitations of ground-based observations, data of vertical distribution of haze aerosols have still been difficult to achieve although it is an important part that cannot be neglected in estimating aerosol radiative forcing and its associated climate impacts (Claquin et al., 1998; Huang et al., 2008; Geng et al., 2011).

The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) that was launched in 2006 can observe aerosols beneath thin clouds and provide aerosol profiles reflecting vertical structures over regional and global scales (Anselmo et al., 2005; Geng et al., 2011) while the data have mainly been exploited to analyze dust aerosols hitherto (Chen et al., 2010; Deng and Zhang, 2016; M. Wang et al., 2015; W. Wang et al., 2015; Wang et al., 2017) over northwestern China and researches on combining CALIPSO data with radiosonde data in the YRD area have still rarely been reported, which yet can endow us with two different opposite view angles on aerosols during haze periods when CALIPSO detects them straight down from sky to ground while radiosonde straight up from ground to sky.

Therefore, in this paper, we employed ground observations, satellite detection and aerological soundings to explore variation of haze events occurred over the YRD region, vertical structure of aerosol optical properties and meteorological factors in the boundary layer when haze formed, respectively. These analyses depict a new picture on haze and aerosols in the YRD so as to provide scientific basis for haze forecast.

1. Data and methods

1.1. Study domain

Seventeen meteorological stations (10 in Jiangsu Province, 2 in Shanghai municipality and 5 in Zhejiang Province) were selected to cover the area from 117.09°E to 121.27°E and 28.37°N to 34.17°N that represents the majority of the YRD area (Fig. 1a).

1.2. Ground observations and radiosonde data

All ground observations, including humidity and visibility, and radiosonde data, covering wind speed, direction, temperature and dew point temperature difference, from January 1981 to December 2016 of 18 meteorological stations (Fig. 1a), obtained from the China Meteorological Data Service Center and the Data Center of Ministry of Environmental Protection of China, were used to identify haze. Ground observations were operated four times a day at Beijing Time 02:00, 08:00, 14:00 and 20:00, respectively while radiosonde data were attained at Beijing Time 00:00 and 12:00 only.

1.3. CALIPSO data

CALIPSO Level 2 Aerosol Profile Data Product both in daytime and nighttime condition from January 2014 to June 2016, including total backscatter coefficient (TBC) at 532 nm, particulate depolarization ratio (PDR) and backscatter coefficient at 1064 nm were utilized.

PDR is defined as the ratio of the perpendicular and parallel components of particulate backscatter coefficient at 532 nm, which displays the degree of irregularity of the detected particles; the higher the PDR is, the more irregular the particles are. Color ratio (CR) is defined as the ratio of backscatter coefficient at 1064 nm and that at 532 nm, reflecting the size of aerosols; the higher the CR is, the larger the particles are (Anselmo et al., 2005; Geng et al., 2011).

1.4. Methodology

After checking the data quality to ensure integrity and consistency, according to the statistical method of haze (China Meteorological Administration, 2010), we firstly summarized the 30-year spatial–temporal characteristics of haze in 12 stations (Fig. 1b) of the YRD between 1981 and 2010 and sifted 190 haze events from January 2014 to June 2016. Then the meteorological factors of 7 stations (Xuzhou, Sheyang, Nanjing, Baoshan, Hangzhou, Quzhou and Hongjia) and vertical distribution of aerosol optical properties during haze episodes were analyzed based upon the radiosonde data and CALIPSO, respectively.

2. Results and discussions

2.1. Spatial–temporal characteristics of haze

If there is no precipitation, dust storm, blowing sand, floating dust, smoke, blowing snow and snow storm on one certain day, meanwhile, visibility and relative humidity are below 10 km and 80%, respectively, then we determine it as one "haze day". Variation of 30-year accumulated haze days (Fig. 1b) illustrates that the frequency of haze events between the period of 1981 and 2010 decreased generally from north to south over the YRD region although with an episodic steady growth in Zhejiang Province, reaching at the lowest point

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