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Space-borne observations of aerosol - cloud relations for cloud systems of different heights

S. Stathopoulos *, A.K. Georgoulias, K. Kourtidis

Laboratory of Atmospheric Pollution and Pollution Control Engineering of Atmospheric Pollutants, School of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece

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ABSTRACT

Here, we examine the aerosol - cloud relations over three major urban clusters of China, representative of three different climatic regimes, under different water vapor conditions and cloud heights, using Aerosol Optical Depth at 550 nm (AOD), Cloud Fraction (CC), Cloud Optical Depth (COD), Water Vapor (WV) and Cloud Top Pressure (CTP) data from the MODIS instrument. Over all regions and for all seasons, CC is found to increase with increasing AOD, WV and cloud height. Aerosols, at low WV environments and under constant CTP, have less impact on CC than at high WV environments. Furthermore, AOD has a varying influence on COD depending on CTP. Finally, COD is found to increase with height for low and middle height clouds, and with increasing AOD, especially at low AOD. Our results demonstrate that the role of WV in the observed satellite-based aerosol - cloud relations is significant for all cloud heights.

1. Introduction

Aerosols affect climate both directly, by scattering and absorbing the incoming solar radiation, and indirectly, by altering the cloud microphysical processes. The overall effect of these processes is the reduction of solar radiation reaching the Earth's surface, the stabilization of the boundary layer by heating the aerosol layer in the presence of absorbing aerosols and deceleration of the water cycle in the atmosphere (Ackerman et al., 2000; Jacobson, 2002; Kaufman et al., 2002; Koren et al., 2004; Koren et al., 2005; Ramanathan et al., 2005). Increasing aerosols cause an increase in the cloud droplet number concentration and a simultaneous decrease in the droplet size under constant liquid water content, known as the “first indirect effect” or “Twomey effect” (Twomey, 1974). This decrease in droplet size affects the precipitation efficiency, causing an increase in liquid water content, cloud lifetime and cloud cover, known as the “second indirect effect” or “cloud lifetime effect” (Albrecht, 1989). Aerosol indirect effects are highly dependent on the aerosol type, their vertical and size distribution and meteorological conditions (Dusek et al., 2006; Matsui et al., 2006; Yuan et al., 2008). Furthermore, the presence of absorbing aerosols may suppress cloud formation by reducing the moisture available for cloud growth, known as semi-direct effect (Hansen et al., 1997; Koch and Del Genio, 2010). So, aerosols may invigorate or suppress horizontal and vertical cloud development, depending on their radiative and microphysical effects, and the cloud type (Li et al., 2012). Hygroscopic aerosols are expected to lead to enhancement, while absorbing aerosols to suppression (Peng et al., 2016). Apart from the aerosol direct and indirect effects, the observed aerosol - cloud relations are dependent on retrieval errors and meteorological conditions (see Quaas et al., 2010 for details).

China is one of the most populated and aerosol impacted regions in the world (Duncan et al., 2003; Li C. et al., 2007), primarily, a result of human activities (construction, traffic, agriculture, etc.) (Lei et al., 2011; Streets et al., 2008) but also of biomass burning and dust storms from the arid regions (deserts) in Northwestern China (Jin and Shepherd, 2005; Zhao and Li, 2007). Specifically, sulfates, dust and carbonaceous aerosols exhibit the highest concentrations over the region (Guo et al., 2011). In addition, the decline of the surface monsoon winds over the past 50 years was found to decrease the removal rate of aerosols over the urban clusters (Jiang et al., 2009). Many studies have investigated aerosol concentrations, as well as their impact on cloud microphysics over different regions of China in the past (Guo et al., 2009; Wang et al., 2014; Wang et al., 2011). Here we focus our investigation over three such urban clusters, namely the Beijing - Tianjin - Hebei urban cluster (BTH), the Yangtze River Delta urban cluster (YRD) and the Pearl River Delta urban cluster (PRD) (Fig. 1). These regions experienced an impressive population growth and a rapid industrial development the last two decades with a consequent enhancement of anthropogenic aerosol and trace gas emissions (see Kourtidis et al., 2015). Over these regions, generally, aerosols, tend to accumulate near the boundary layer (BL), and then gradually decrease with altitude (Wang et al., 2015).

This work, complements a recent study on the aerosol-cloud relations over the three urban clusters (Kourtidis et al., 2015), by taking

* Corresponding author at: Laboratory of Atmospheric Pollution and Pollution Control Engineering of Atmospheric Pollutants, School of Engineering, Democritus University of Thrace, 12 Vas. Sofias str., 67100 Xanthi, Greece.

E-mail addresses: sstathop@env.duth.gr (S. Stathopoulos), argeor@env.duth.gr (A.K. Georgoulias), kourtidi@env.duth.gr (K. Kourtidis).

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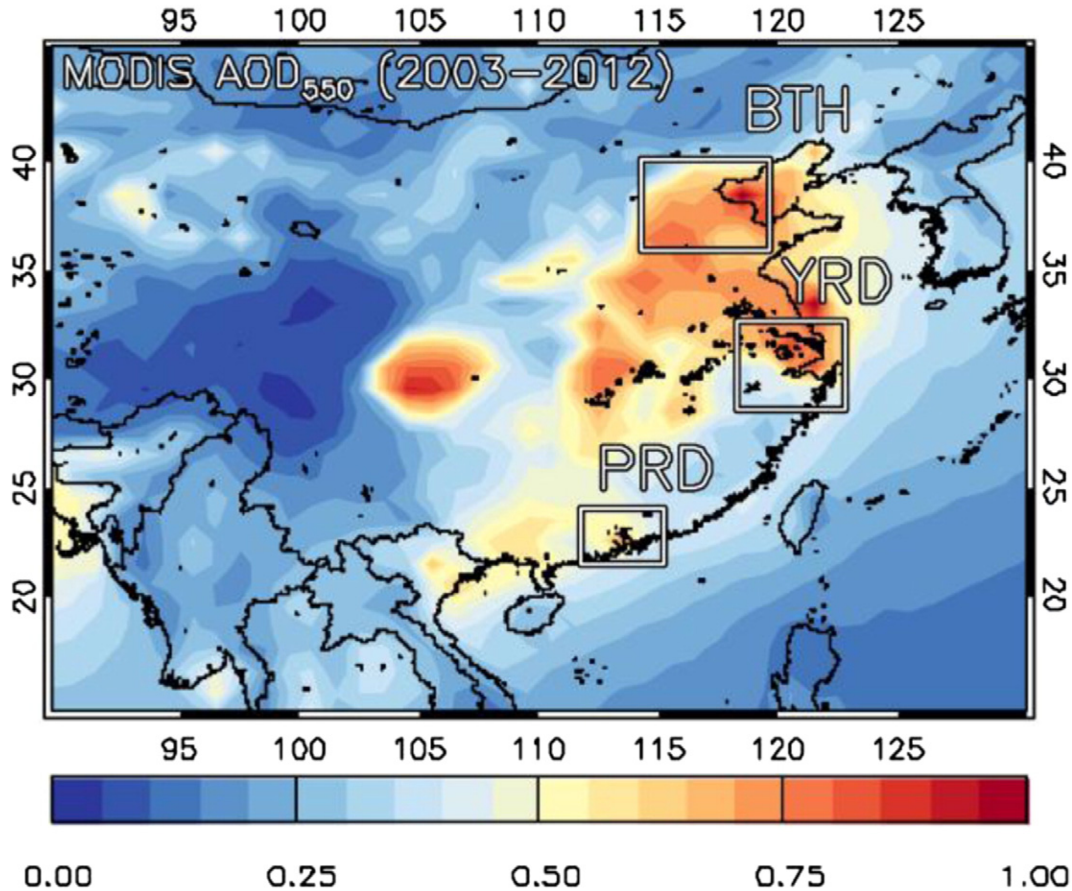

Fig. 1. Map with the mean MODIS AOD over China for the period 2003–2012, and the three urban clusters studied here (BTH: Beijing - Tianjin - Hebei urban cluster, YRD: Yangtze River Delta urban cluster, PRD: Pearl River Delta urban cluster).

into account not only the horizontal but also the vertical development of clouds as manifested by CTP and COD. As shown in Kourtidis et al. (2015), atmospheric water vapor (WV) plays a determinant role in the observed aerosol - cloud relations. The aim of this paper is to study the interrelations of aerosols and water vapor with cloud optical properties for cloud systems of different heights during different seasons. For this purpose, space-borne aerosol (AOD) and cloud properties (CC, COD, CTP), along with WV retrieved from the MODIS sensors onboard Terra and Aqua satellites, are utilized.

2. Data and methods

The Asian Monsoon system and the Tibetan Plateau influence the climate of China greatly, bearing a decisive effect on the rainy seasons across the country (Ding and Murakami, 1994; Domrös and Peng, 1988; Ye and Gao, 1979; Yihui and Chan, 2005; Zhang et al., 2012). In particular, Asian Monsoons start with the pre-monsoonal rain period over South China in early April and lasts from May until August. The summer monsoon rain belt propagates northward to the Yangtze River basin in June and finally shifts to northern China in July. In August, the monsoon period ends and the rain belt moves back to southern China. According to Song et al. (2011), under the influence of Asian Monsoon, China can be divided into five climate regions: (i) temperate monsoon, (ii) subtropical monsoon, (iii) tropical monsoon, (iv) temperate continental and (v) plateau/mountain climate region. Here, we selected three urban clusters representative of three different climate regions; the BTH urban cluster (35.5°–40.5° N, 113.5°–120.5° E) as a temperate monsoon climate region, the YRD urban cluster (28.5°–33.5° N, 117.5°–123.5° E) as a subtropical monsoon climate region and the PRD urban cluster (21.5°–24.5° N, 111.5°–115.5° E) as a tropical monsoon climate region within the Inter-Tropical Convergence Zone (ITCZ) migration belt (Fig. 1). The BTH region is characterized by severe haze pollution episodes, due to coal combustion emissions for heating and stagnant meteorological conditions, especially in winter (Sun et al., 2013). These meteorological conditions involve low wind speed, high humidity and a shallow boundary layer. (Zhao et al., 2013). The YRD region is governed by cool and dry winters, and hot and humid summers. According to Li et al. (2011), air quality in winter is generally worse than in summer, mainly because of the unfavorable meteorological dispersion conditions. Finally, the PRD region, is where haze episodes occur more frequently, due to high aerosol concentrations (Deng et al., 2008). These aerosols may heat the atmosphere, generate a cyclonic circulation anomaly, and therefore affect the fog formation in southern and eastern-central China (Niu et al., 2010).

The Moderate Resolution Imaging Spectroradiometer (MODIS), onboard Terra (launched in late 1999) and Aqua (launched in early 2002) satellites, observes the Earth from a height of approximately 700 km, measuring reflected solar radiance and terrestrial radiation in 36 spectral bands with a spatial resolution ranging from 250 m to 1 km. Its swath is approximately 2300 km, nearly covering the entire globe daily (Levy et al., 2007). The standard MODIS aerosol algorithm (Dark Target) over land chooses from a set of fine-dominated aerosol models and a single coarse-dominated aerosol model (Kaufman et al., 1997; Levy et al., 2010; Remer et al., 2005). Its retrievals are based on aerosol scattering and use visible and near-IR channel measurements over the globe (Chu, 2002; Kaufman et al., 1997; Remer et al., 2005) except for bright land surfaces where the Deep Blue algorithm is used instead (Hsu et al., 2004). A third algorithm is used over oceanic regions (Remer et al., 2005; Tanré et al., 1997).