Atmospheric Environment xxx (2015) 1–9

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Ground-based remote sensing of aerosol climatology in China: Aerosol optical properties, direct radiative effect and its parameterization

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HIGHLIGHTS

- A high-quality database of aerosol optical properties in China was established.
- An empirical relationship of AOD and SSA to ADRE has been introduced.
- Spatio-temporal variation of aerosol optical properties and ADRE was revealed.

ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
3 February 2015
Accepted 30 May 2015
Available online xxx

Keywords:
Aerosol
Optical properties
Aerosol direct radiative effect

ABSTRACT

Spatio-temporal variation of aerosol optical properties and aerosol direct radiative effects (ADRE) are studied based on high quality aerosol data at 21 sunphotometer stations with at least 4-months worth of measurements in China mainland and Hong Kong. A parameterization is proposed to describe the relationship of ADREs to aerosol optical depth at 550 nm (AOD) and single scattering albedo at 550 nm (SSA). In the middle-east and south China, the maximum AOD is always observed in the burning season, indicating a significant contribution of biomass burning to AOD. Dust aerosols contribute to AOD significantly in spring and their influence decreases from the source regions to the downwind regions. The occurrence frequencies of background level AOD (AOD < 0.10) in the middle-east, south and northwest China are very limited (0.4%, 1.3% and 2.8%, respectively). However, it is 15.7% in north China. Atmosphere is pristine in the Tibetan Plateau where 92.0% of AODs are <0.10. Regional mean SSAs at 550 nm are 0.89–0.90, although SSAs show substantial site and season dependence. ADREs at the top and bottom of the atmosphere for solar zenith angle of $60 \pm 5^{\circ}$ are -16–-37 W m^{-2} and -66–-111 W m^{-2}, respectively. ADRE efficiency shows slight regional dependence. AOD and SSA together account for more than 94 and 87% of ADRE variability at the bottom and top of the atmosphere. The overall picture of ADRE in China is that aerosols cool the climate system, reduce surface solar radiation and heat the atmosphere.

1. Introduction

As the most populated and fastest developing country of the world, rapid economic growth in China leads to gradual drops in atmospheric environment (Li et al., 2007, 2011a). Recent studies suggested that increased aerosol loading might have significant

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http://dx.doi.org/10.1016/j.atmosenv.2015.05.071
1352-2310/© 2015 Published by Elsevier Ltd.

effects on weather and climate. For example, surface global and direct solar radiation decreased by about 8.6% and 4.6% per decade during 1961–2000 (Qian et al., 2006). Aerosols are likely the major driver of the cooling trend in the Sichuan Basin and central eastern China (Li et al., 1995). Aerosol effects on clouds could induce large changes in precipitation patterns, which in turn might change not only regional water resources, but also change the regional and global circulation systems (Qian et al., 2009; Li et al., 2011b). Aerosols, clouds and their interactions with climate are still the most uncertain areas of climate change and require multidisciplinary coordinated research efforts.

Tropospheric aerosols are highly variable in time and space. Comprehensive understanding of aerosol optical properties is a foundation for further understanding of the aerosol-cloud-radiation interactions and thereby an important base to reduce the uncertainty of aerosol's weather-climate effects (Huang et al., 2006a,b). Ground-based remote sensing of aerosol optical properties using sunphotometer is approved to be an important method to accurately characterize aerosol optical properties owing to its wide angular and spectral measurements of solar and sky radiation (Dubovik et al., 2002). The data are widely used to reveal spatio-temporal variation of aerosol optical properties, to evaluate satellite and model aerosol products, and to study aerosol-cloud-radiation interactions (Holben et al., 2001).

2. Past research in ground based remote sensing of aerosol optical properties in China

Sunphotomter has been used to observe aerosol since the beginning of 1980s in China (Mao et al., 2002). Aerosol optical depth (AOD) at 500 nm in Beijing during July 1980 to July 1981 ranged from 0.31 (September) to 0.65 (May) (Zhao et al., 1983). Lu et al. (1981) proposed to retrieve aerosol size distribution from simultaneous measurements of spectral extinction and forward scattering radiation. A field campaign was carried out in winter of 1981 to test this proposal, which showed that aerosol size distribution within 0.1–10 μm could be retrieved (Qiu et al., 1983). Qiu and Zhou (1986) further studied information content of sky radiance with regard to the aerosol size distribution, refractive index and surface reflectance. Aerosol refractive index was retrieved from sky radiance measurement in Beijing to be 1.517−0.034*i* and 1.533−0.016*i* during the heating and not-heating period, respectively (Li and Mao, 1989).

Much progress has been made since the ending of 1990s. One year of AOD measurements at four stations were made (Zhang et al., 2002). Several SKYNET stations have been established since the beginning of 2000s as a result of an international cooperation (Shi et al., 2005). Extensive measurements of AOD at four wavelengths have been made with handheld sunphotometers at 24 stations starting since august 2004 (Xin et al., 2007). The data were used to reveal spatial-temporal variation of AOD and to classify aerosol types (Wang et al., 2011). Aerosol single scattering albedo (SSA) at 500 nm was retrieved from AOD and satellite measured reflected radiance at the top of the atmosphere (TOA). The nationwide means of SSA at 500 nm in 2005 was 0.89 ± 0.04 (Lee et al., 2007).

In spring of 2001, four Aerosol Robotic Network (AERONET) stations have been established in North China for the first time. Aerosol optical properties in dust source region were compared with that in the downwind regions and potential variations of aerosol optical properties were studied (Cheng et al., 2006). Since spring of 2002, more than 30 AERONET stations have been established across China. Long-term measurements have been made at several AERONET stations, for example, at Beijing since April 2002, at Xianghe since September 2004 and at Taihu since September 2005 (Li et al., 2007), as well as at Lanzhou (SACOL) since July 2006 (Huang et al., 2008a,b). Furthermore, China Aerosol Research Network (CARSNET) with more than 20 stations was established in 2002 by the Chinese Meteorological Bureau (Che et al., 2009). Climatology of aerosol optical properties and aerosol direct radiative effects (ADRE) were studied on the basis of these measurements. For example, a distinct seasonal variation of AOD and SSA was observed in Beijing, i.e., higher values in summer and lower in winter, which was quite different from surface aerosol concentration (Xia et al., 2006). Spring maximum AOD in the northwestern China was observed in spring (Bi et al., 2010). Dust aerosol's absorption and atmospheric heating by dust absorption in the Taklimakan Desert was estimated (Ge et al., 2011; Huang et al., 2009).

The objective of this study is to present the spatio-temporal variation of aerosol optical properties based on aerosol optical data at 21 sunphotometer stations with at least four months' worth of measurement. This is the first attempt to combine ground-based remote sensing data as many as possible to reveal spatio-temporal variability of aerosol optical properties in China. Distinct seasonal variation of aerosol optical properties is firstly revealed. Analysis of aerosol direct radiative effect at the bottom (BOA) and top of the atmosphere is then performed. Finally, a parameterization of the relationship of ADRE to AOD and SSA at 550 nm (AOD and SSA hereafter if not specified) is established. The paper is organized as follows. Site and data are described in following section. Section 3 presents seasonal variation of aerosol optical properties in different regions of China. A parameterization is proposed in Section 4 to reveal how ADRE varies with AOD and SSA. Section 5 summarizes the research and the major results.

3. Site and data

Aerosol optical data at forty-two sunphotomter stations with at least one month of measurements are available. In order to present climatological aspect of spatio-temporal variation of aerosol optical properties, 21 stations with more than four months of measurements are used. Taking the predominant aerosol types and the proximity to source areas into account, the stations have been grouped into 5 regions, i.e., R1: south and southwest China; R2: the middle-east China; R3: the north and northeast China; R4: The northwest region; R5: The Tibetan Plateau (Fig. 1). Table 1 summarized information on all stations.

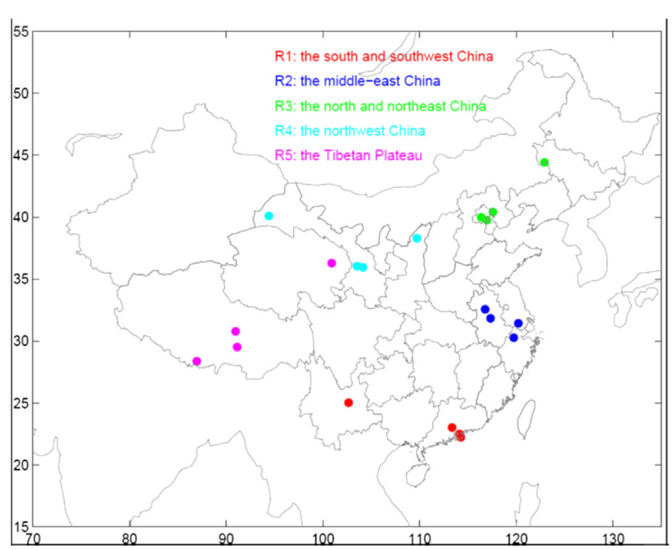

Fig. 1. Spatial distribution of sunphotometer stations. The stations are grouped into five regions, i.e., R1: south and southwest China; R2: the middle-east China; R3: the north and northeast China; R4: the northwest China; and R5: the Tibetan Plateau.

Please cite this article in press as: Xia, X., et al., Ground-based remote sensing of aerosol climatology in China: Aerosol optical properties, direct radiative effect and its parameterization, Atmospheric Environment (2015), http://dx.doi.org/10.1016/j.atmosenv.2015.05.071