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Optical properties and radiative forcing of urban aerosols in Nanjing, China☆

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HIGHLIGHTS

- Aerosol characteristics, optical properties and DRF were analyzed in urban Nanjing.
- BC accounted for about 6.6 ± 2.9% of $PM_{2.5}$ in urban Nanjing from Jan to Apr 2011.
- Wavelength-dependent surface albedo of MODIS was used when accessing aerosol DRFs.
- Annual 550 nm AOD was 0.04 and 0.6 for absorbed and total aerosols in Nanjing (NJ).
- Clear sky DRF of NJ-absorbed and total aerosols was +4.5 and −6.9 W m^{-2} at the TOA.

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ABSTRACT

Continuous measurements of atmospheric aerosols were made in Nanjing, a megacity in China, from 18 January to 18 April, 2011 (Phase 1) and from 22 April 2011 to 21 April 2012 (Phase 2). Aerosol characteristics, optical properties, and direct radiative forcing (DRF) were studied through interpretations of these measurements. We found that during Phase 1, mean $PM_{2.5}$, black carbon (BC), and aerosol scattering coefficient (Bsp) in Nanjing were 76.1 ± 59.3 μg m^{-3}, 4.1 ± 2.2 μg m^{-3}, and 170.9 ± 105.8 M m^{-1}, respectively. High pollution episodes occurred during Spring and Lantern Festivals when hourly $PM_{2.5}$ concentrations reached 440 μg m^{-3}, possibly due to significant discharge of fireworks. Temporal variations of $PM_{2.5}$, BC, and Bsp were similar to each other. It is estimated that inorganic scattering aerosols account for about 49 ± 8.6% of total aerosols while BC only accounted for 6.6 ± 2.9%, and nitrate was larger than sulfate. In Phase 2, optical properties of aerosols show great seasonality. High relative humidity (RH) in summer (June, July, August) likely attributed to large optical depth (AOD) and small Angstrom exponent (AE) of aerosols. Due to dust storms, AE of total aerosols was the smallest in spring (March, April, May). Annual mean 550-nm AOD and 675/440-nm AE were 0.6 ± 0.3 and 1.25 ± 0.29 for total aerosols, 0.04 ± 0.02 and 1.44 ± 0.50 for absorbing aerosols, 0.48 ± 0.29 and 1.64 ± 0.29 for fine aerosols, respectively. Annual single scattering albedo of aerosols ranged from 0.90 to 0.92. Real time wavelength-dependent surface albedo from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to assess aerosol DRFs. Both total and absorbing aerosol DRFs had significant seasonal variations in Nanjing and they were the strongest in summer. Annual mean clear sky TOA DRF (including daytime and nighttime) of total and absorbing aerosols was about −6.9 and +4.5 W m^{-2}, respectively. Aerosol DRFs were found to be sensitive to surface albedo. Over brighter surfaces, solar radiation was more absorbed by absorbing aerosols and less scattered by scattering aerosols.

1. Introduction

Atmospheric aerosols can influence global and regional climate significantly and their loadings have substantially increased since preindustrial times (Qin et al., 2001). Kiehl and Briegleb (1993)

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suggested that the sulfate aerosol direct effect could greatly offset the warming effect of CO_2 in regions with high sulfate concentrations and Jacobson (2002) emphasized the warming effect of black carbon (BC) as it is only preceded by CO_2, implying the importance of atmospheric aerosols on the global energy budget.

Aerosol optical and radiative properties at global and regional scales have been studied since 1990s with model simulations (Penner et al., 2001; Liao and Seinfeld, 2005; Zhuang et al., 2013a) and satellite/surface-based retrievals (Bellouin et al., 2003; Zhang et al., 2005; Christopher et al., 2006; etc.). Furthermore, uncertainties of internally/externally mixing states in estimating aerosol direct radiative forcings (DRFs) have been assessed with numerical models in the last decade (Jacobson, 2001; Kim et al., 2008; Zhuang et al., 2013b). Forster et al. (2007) estimated that the global mean aerosol DRF at the top of atmosphere (TOA) is about -0.55 W m^{-2}, derived from the ground observations, while the DRF value is positive from model simulation, i.e., $+0.04$ to -0.63 W m^{-2}. Reddy et al. (2005) suggested that the global mean simulated DRF of anthropogenic and natural aerosols at the TOA was about -2.1 W m^{-2} in clear sky. At region scale over East Asia, simulated DRF at the TOA is from -6.77 to -3.43 W m^{-2} for total aerosols (Huang et al., 2007), $+0.81$ W m^{-2} for BC (Zhuang et al., 2013a), and -0.88 W m^{-2} for nitrate (Wang et al., 2010). Generally, aerosol DRFs derived from ground observations have relatively lower uncertainties in comparison with those from simulations. Ramanathan and Carmichael (2008) found poorer performances in model simulations of aerosols over Southern Asia compared with observations. Recently, more and more observations have been used to study regional aerosol optical and radiative properties (Yu et al., 2006). For examples, Markowicz et al. (2008) found that the daily mean surface DRF can exceed -20 W m^{-2} in Persian Gulf region. Khatri et al. (2009) reported that summer aerosols in Nagoya have a high absorbing ability, resulting in a positive DRF of $+2.5$ W m^{-2} at the TOA and a very negative forcing of -71.8 W m^{-2} at the surface. In Kuhlmann and Quaas (2010), shortwave radiation was found to be reduced by 20–30 W/m^2 due to aerosol perturbation over Qinghai-Tibet Plateau. Alam et al. (2011) derived a mean aerosol DRF about -22 ± 6 W m^{-2} at the TOA in Karachi from observations.

China is one of the main source regions for atmospheric aerosols in the world. Aerosols over China vary complicatedly in compositions and distributions. Aerosols emit strongly in central, southwestern, and eastern China, including Yangtze River Delta (YRD) and Pearl River Delta regions (Zhang et al., 2009), one of the fastest growth regions over China. Although the aerosol direct effects over China have been studied in numerical simulations (Wu and Fu, 2005; Han et al., 2009, 2012, 2011; Han, 2010; H. Zhang et al., 2012) and in observations (Xia et al., 2007; Wang et al., 2009; Li et al., 2010; Yan et al., 2010; Cai et al., 2011; Bai et al., 2011; Xiao et al., 2011; Zhou et al., 2011), none of them derived the optical properties and DRF of urban aerosols in YRD from observations.

The objective of this study is to better understand the characteristics, optical properties, and DRFs of urban aerosols in YRD, with interpretations of short-term (three months) measurements of BC, aerosol scattering coefficient (Bsp), and particulate matters with diameter of 2.5 μm or less ($PM_{2.5}$) and long-term (one year) measurements of aerosols optical depth (AOD) and Angstrom exponent (AE) at an urban site in Nanjing, YRD. A column radiative transfer model, Tropospheric Ultraviolet–Visible radiation model (TUV) (Madronich, 1993) was employed to calculate clear sky aerosol DRFs at the TOA and the surface. In previous studies, surface albedo for solar broadband or visible albedo was often used in estimating aerosol DRFs (Ma and Yu, 2012). In this study, wavelength-dependent surface albedo from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument was used.

This paper is organized as follows. The method including the measurements and the radiation transfer model TUV is described in Section 2. The measured data are interpreted in Section 3, regarding the characteristics of aerosols in Nanjing in Section 3.1, optical properties of aerosols in Section 3.2, and aerosol direct radiative forcing Section 3.3. Conclusions are provided in Section 4.

2. Methods

2.1. Observation site, instrument and data introductions

Nanjing is the capital city of the Jiangsu province, a typical developing city of YRD. The sampling site is located in the downtown area of the city inside the Gulou campus of Nanjing University, at 32.05 °N, 118.78 °E, with the altitude of 99.3 m (79.3 m building tall plus 20 m asl), There are no higher buildings near or around the site. More details about the station are available in Zhu et al. (2012).

Short-term measurements of $PM_{2.5}$, BC and Bsp were made from 18 January 2011 to 18 April 2011 (defined as Phase 1). These three variables were measured with TEOM particulate mass monitor-Series 1400, Aethalometer (AE-31), and Integrating Polar Nephelometer with $PM_{2.5}$ size-cut inlet sensors (NGN-3A) (shown in Table 1). To obtain the compositions of total aerosols, Ambient Eight Stage Cascade Impactor Sampler was used.

Total aerosols AOD and AE were measured for a longer period from 22 April 2011 to 21 April 2012 (defined as Phase 2) using a Cimel sunphotometer CE-318N. Additionally, single scattering albedo (SSA) of total aerosols and AODs of absorbing, fine, and coarse aerosols could be inversed by DOBVIC algorithm which has been used in Aerosol Robotic Network (AERONET).

Relative humidity was measured with a conventional meteorological instrument at the site. Wind direction and speed were acquired from the national meteorological station which is about 1.5 km far away from the site.

Table 1
Introductions on the sampling instruments of aerosols.

Instruments	Factor (unit)	Method	Range	Resolution	Accuracy
I1	$PM_{2.5}$ mass (μg m^{-3})	A tapered element oscillating microbalance	>0.01 μg m^{-3}	0.01 μg m^{-3}	1 min
I2	BC mass (μg m^{-3})	Attenuation of transmitted light through membrane with BC	0–1 mg m^{-3}	0.001 μg m^{-3}	5 min
I3	Bsp (M m^{-1})	Irradiation to the particles of sampling gases using internal light source	0.1–3276.8 M m^{-1}	0.1 M m^{-1}	2 min

I1TEOM particulate mass monitor, Series 1400.
I2Aethalometer (AE-31).
I3Integrating Polar Nephelometer with $PM_{2.5}$ size-cut inlet sensors (NGN-3A).