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A critical assessment of direct radiative effects of different aerosol types on surface global radiation and its components

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A critical assessment of direct radiative effects of different aerosol types on surface global, direct and diffuse radiation is presented. The analysis is based on measurements of aerosol optical properties and surface solar radiation (SSR) of cloud-free days at the Baseline Surface Radiation Network (BSRN) and Aerosol Robotic Network station (AERONET) of Xianghe over the North China Plain between October 2004 and May 2012. Six aerosol types are classified based on aerosol size and absorption from the AERONET retrieval products, including two coarse-mode dominated aerosol types: dust (DU: fine mode fraction (FMF) <0.4) and polluted dust (PD: FMF within 0.4–0.7) and four fine-mode dominated aerosol types (FMF >0.7) but with different single scattering albedo (SSA): highly absorbing (HA: SSA <0.85), moderately absorbing (MA: SSA within 0.85–0.90), slightly absorbing (SA: SSA within 0.90–0.95) and very weakly absorbing (WA: SSA $>$ 0.95). Dramatic differences in aerosol direct radiative effect (ADRE) on global SSR and its components between the six aerosol types have been revealed. ADRE efficiency on global SSR for solar zenight angle (SZA) between 55° and 65° ranges from -106 W m^{-2} for WA to -181 W m^{-2} for HA. The minimum ADRE efficiency on diffuse SSR is derived for HA aerosols, being 113 W m^{-2} that is about half of that by DU, the maximum value of six aerosol types. ADRE efficiency on global SSR by DU and PD (-141 to -150 W m^{-2} for SZA between 55° and 65°) is comparable to that by MA, although 100 W m^{-2} more direct SSR is extincted by DU and PD than by MA. DU and PD induce more diffuse SSR than MA that offsets larger reduction of direct SSR by DU and PD. Implications of the results to related researches are detailed discussed. The results are derived from aerosol and radiation data in the North China Plain, however the method can be used to any other stations with similar measurements.

1. Introduction

Tropospheric aerosols are minute particles suspended in the troposphere that scatter and absorb sunlight. Their extinction of sunlight can result in a reduction of surface solar radiation (SSR), which has the potential to be interesting in global warming, water cycling and solar energy application, just to name a few [1]. Both natural and anthropogenic processes produce aerosols that vary in size and composition and thereby in their optical properties. Emissions of aerosols into the troposphere from the major sources include sulfates from the oxidation of sulphur-containing gases, nitrates from gaseous nitrogen species, organic materials from biomass combustion and oxidation of volatile organic compounds, soot from combustion, and mineral dust from Aeolian processes. Natural aerosols are generally composed of these aerosol species but vary with their percentages. Owing to the short lifetime of aerosol

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particles in the tropospheric atmosphere, and the non-uniform distribution of sources, their geographical distribution is highly non-uniform. As a consequence, the relative importance of the numerous sources shows considerably spatial and temporal variations, which results in substantial variation of aerosol optical properties across the world [2].

The North China Plain (NCP) is a densely populated region of the world and has experienced unprecedented economic and population growth during the past three decades, which has resulted in a remarkable increase of anthropogenic aerosols [3,4]. Additionally, the dust originates in the deserts and Gobi deserts of Mongolia, northern China and Kazakhstan where dense clouds of fine, dry soil particles are sporadically emitted into the atmosphere under favorable weather conditions. These dust clouds are then carried eastward by prevailing winds and pass over the NCP [5]. Physical and optical properties between dust and anthropogenic aerosols are quite different. Dust aerosols are major coarse particles that absorb solar radiation in the ultraviolet range more than in the visible spectrum [6,7]. Anthropogenic aerosols are major fine-mode particles and their optical properties are highly dependent on their physical and chemical properties. The mixture of coarse dust particles and anthropogenic pollution has resulted in a rather complex nature of aerosol physical and optical properties [8]. The external linear mixing of both fine- and coarse-mode components dominates variations in the complex refractive index and single scattering albedo (SSA) in spring and winter when the fine-mode fraction of extinction is less than about 0.6 [6,9]. The complexity of aerosols in the NCP provides us a natural laboratory to study how aerosols affect SSR. More importantly, we can learn how aerosol effects on SSR vary with aerosol types.

Sunphotometer has been widely used to investigate various column-integrated aerosol properties. The Aerosol Robotic Network (AERONET) program provides a long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties across the world for aerosol characterization research, validation of satellite retrievals, and synergism with satellite and model databases [6,10,11]. The AERONET station has been established since the beginning of this century in the Beijing and Xianghe, an urban and a suburban station in the NCP. More importantly, continuous SSRs have been measured since the fall of 2004, which provides use a good opportunity to study aerosol effects on SSR via its scattering and absorption, not only on global SSR, but also on its components, i.e., direct and diffuse SSR. Aerosol direct effects on global and diffuse SSR were detailed studied in Refs. [12,13]. However, there was still no attempt reported in the literature, as far as I know, to reveal considerable difference in aerosol effects on SSR by different aerosol types, which, however, has the potential to be interesting in researches such as aerosol effects on plant production, carbon cycling and solar energy application.

2. Site, data and methodology

2.1. Site

The sunphotometer and a set of pyranometers were established in fall of 2004 at Xianghe (XH) station, a suburban station in the NCP. XH, a county of Hebei Province close to Beijing, is characterized by agricultural land and light industries. The site experiences both natural aerosols and anthropogenic urban and rural pollutants depending on meteorological parameters such as wind speed, rainfall, relative humidity, cloud amount and type [14].

2.2. Data

2.2.1. AERONET data

The CIMEL sunphotometer, which is the standard instrument of the AERONET, is able to measure direct radiation from the sun at wavelengths ranging from 340 nm to 1020 nm and the angular distribution of sky radiance at four wavelengths (440, 675, 870, and 1020 nm). In addition to the continuous cloud-screened measurements of aerosol optical depth (AOD) with an accuracy of 0.01–0.02 [10,15], the inversion algorithm retrieves aerosol physical and optical properties from the spectral AODs and almucantar scans of radiances as a function of scattering angle, such as aerosol size distribution, aerosol complex refractive index, SSA (the ratio of scattering to extinction), and asymmetry factor (ASY) at four wavelengths. The aerosol inversion algorithm was developed by Dubovik and King [16] and was then further improved to take into account non-spherical shapes of aerosol particles [17,18]. The AERONET inversion algorithm also calculates SSR and aerosol direct radiative effect (ADRE) using the DISORT module with the retrieved aerosol size distribution and complex refractive index as inputs [19]. ADRE is defined here as follows:

$$ADRE = SSR_{WA} - SSR_{NA}, \quad (1)$$

where SSR_{WA} and SSR_{NA} represent SSR with and without the presence of aerosols in the atmosphere, respectively. The ADRE efficiency is defined for the case of no aerosols relative to the value at AOD at 550 nm of 1.0.

2.2.2. Radiation data

An aerosol–radiation–cloud platform was established at XH in September 2004 as part of the “East Asian Study of Tropospheric Aerosols: an International Regional Experiment” project (EAST-AIRE) [14], and has since taken continuous measurements of various radiative and aerosol quantities. SSR was measured by both independent and redundant pyranometers for quality control purposes. Kipp and Zonne's CM21 and CM11 radiometers were used to measure global SSR, respectively. Diffuse and direct SSRs were measured by a black and white pyranometer and a normal incidence pyrheliometer, both mounted on the solar track. All SSR measurements were taken at a 1-min temporal resolution. The data were quality-checked using the Baseline Surface Radiation Network (BSRN) quality control procedures and then submitted to the BSRN data archive. Measurements of SSR from October 2004 to May 2012 were used in this study.

Clear-sky SSR measurements were firstly collected based on an empirical clear-sky detection algorithm [20] that was modified to cope with the specific conditions under study [12]. The rationale behind this algorithm is