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Column-integrated aerosol optical properties and direct radiative forcing based on sun photometer measurements at a semi-arid rural site in Northeast China

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ABSTRACT

Ground and satellite remote sensing measurements have revealed heavy aerosol loading in China; however, aerosol optical properties and direct radiative forcing in Northeast China – important in climate modeling and remote sensing – have not been widely studied. We studied four years of continuous sun photometer measurements at Tongyu, a typical semi-arid rural site in Northeast China, to better understand column-integrated aerosol optical properties and direct radiative forcing. The annual average aerosol optical depth (AOD) at 500 nm was 0.20 ± 0.26; the Ångström exponent (AE) between 440 and 870 nm was 1.37 ± 0.64; and the single scattering albedo (SSA) at 440 nm was 0.91 ± 0.05. The AOD at this rural site was a quarter of that observed in the polluted North China Plain and Yangtze River Delta regions. Anthropogenic fine-mode particles were the dominant contributor to AOD. The AOD and AE showed generally opposite seasonal variation patterns. Relatively higher AOD values in summer (0.26 ± 0.27) and spring (0.24 ± 0.30) were likely related to long-range transportation of anthropogenic aerosols from southern industrial regions in summer, and the increased contribution of dust events in spring. The minimum AOD (0.16 ± 0.22) was concurrent with the maximum AE (1.75 ± 0.76), observed in winter. On average, the absorption AOD (AAOD) at 440 nm and its absorption Ångström exponent (AAE) between 440 and 870 nm were 0.06 ± 0.03 and 1.04 ± 0.43, respectively. The mean AAE was considerably higher than 1 in autumn and winter, indicating that brown carbon from biomass burning contributed greatly to aerosol absorption. The AAE was lower than 1 in summer and spring, related to the coating of black carbon particles. Large negative aerosol direct radiative forcing was estimated at the bottom of the atmosphere, with relatively lower values estimated at the top of the atmosphere; the means were −26.28 and −9.42 W m^{-2}, respectively. This resulted in a strong cooling effect on the surface, but warming in the atmosphere, potentially impacting the regional climate.

1. Introduction

More than one third of China is covered by arid and semi-arid areas (Fu and An, 2002). The land–atmosphere processes in these regions play an important role in global and regional climate systems, like the East Asian Monsoon circulation (Liu et al., 2008). Changes in climate and climate variability impact the water and energy cycles in these regions (Huang et al., 2008). As a climatic and ecological transitional zone, investigation of semi-arid areas is key to understanding aridification, due to its high sensitivity and vulnerability (Fu and Wen, 2002).

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To further investigate land–atmosphere processes and climate change in semi-arid regions, and the role of human activities, the Tongyu observation station (44.56°N, 122.92°E, 151 m above mean sea level) was established in the northwest part of Jilin Province, China.

Aerosol is a potential climate change agent, but with a low level of scientific understanding because of the highly spatial and temporal variability in its physical/chemical properties and large uncertainties in its radiative forcing (IPCC, 2013). Dust aerosols from arid and semi-arid regions are the main sources of dust in Asia, and significantly impact regional climate via direct radiative forcing, indirect and semi-direct effects on cloud generation, evolution and dissipation (Huang et al., 2006, 2010). Short-term observation of near-surface $PM_{2.5}$ particles, including their chemical composition and optical properties, has been conducted at Tongyu during spring (Zhang et al., 2008, 2012a; Ho et al., 2011; Shen et al., 2011; Wu et al., 2012). Results from these previous studies clearly indicated that, even in the dusty season, anthropogenic aerosol components such as water-soluble ions, black carbon (BC), and organic carbon accounted for a large portion of aerosol loading. This mixture of natural dust and anthropogenic aerosols had a complex impact on radiation and regional climate change (Che et al., 2009a). Extensive long-term observations of physical/optical parameters including aerosol optical depth (AOD), particle size and absorption have been rarely reported in the literature.

Ground-based remote sensing by sun photometry has been validated as a good method to study column-integrated aerosol optical properties in the atmosphere (Dubovik et al., 2000). Such datasets are widely used to study aerosol radiative forcing and its climate effect (e.g., Xia et al., 2007a, 2007b; Che et al., 2014), and to validate satellite remote sensing (e.g., Hsu et al., 1999; Remer et al., 2002; Bréon et al., 2011; Xie et al., 2011) and chemical model simulation results (e.g., Chin et al., 2002; Matthias, 2008; Han et al., 2012). Regional and global networks, such as the China Aerosol Remote Sensing Network (CARSNET) (Che et al., 2009b), and the Aerosol Robotic Network (AERONET) (Holben et al., 1998), have been established in recent decades. The aerosol optical properties revealed by these networks have been intensively reported over certain regions in China, such as the North China Plain (Xia et al., 2007a; Li et al., 2007; Zhu et al., 2014), eastern China (Xia et al., 2007b; Pan et al., 2010) and western desert regions (Xia et al., 2004; Che et al., 2009a). However, similar studies are very limited in Northeast China, especially in the climatically important semi-arid region. Aerosol optical properties, and related radiative effects in a suburban region, northeastern China (Liaozhong), were studied by Xia et al. (2007c) using sun photometer observations over three months. The spatiotemporal variation of AOD and the Ångström exponent (AE) was described by Wang et al. (2010) with four years of sun photometer measurements at a regional background site in Northeast China (Longfengshan); Zhao et al. (2013) also used sun photometer measurements at four stations over urban and industrial regions of Northeast China to conduct similar studies. However, only selected optical parameters, such as AOD, have been analyzed in this region; detailed analysis of aerosol size and absorption, which have decisive impact on radiative forcing, has not taken place.

In this study, the column-integrated aerosol optical properties at Tongyu are investigated based on four years of sun photometer remote sensing measurements. The optical and microphysical properties including the AOD, single scattering albedo (SSA), absorption AOD (AAOD), and volume size distribution, are analyzed in detail. The aerosol direct radiative forcing (ADRF) is also discussed. This work is intended to give a sense of the columnar aerosol optical properties in a typical semi-arid region in Northeast China, and provide essential parameters to increase the accuracy of climate simulations in this sensitive region.

2. Measurements and methods

2.1. Site description

The Tongyu observation station, a typical semi-arid site in Northeastern China, is a reference site of the Coordinated Energy and Water Cycle Observation Project (CEOP), part of the Global Energy and Water Cycle Exchanges Project (GEWEX). The Tongyu station lies in a degraded grassland area, with very few anthropogenic emission sources (Cheng et al., 2010; Wu et al., 2012). Routine meteorological and water vapor flux measurements have been conducted since October 2002. Long-term continuous observations of aerosol optical parameters began in March 2010, including measurements of near-surface aerosol absorption and scattering coefficients, as well as column-integrated parameters.

From the cluster analysis of the 3-day backward trajectories (HYSPLIT Model, Draxler and Rolph, 2013) ended at the Tongyu observation station (500 m above ground level) during the period from March 2010 to February 2014 (Fig. 1), roughly 20% of air masses arriving at Tongyu came from the heavily polluted south. This region includes the Jing-Jin-Ji area, where the fine-particle pollution was severe. Furthermore, airflows from the west likely transported dust aerosols in spring.

2.2. Measurements

As a regional background site of the China Aerosol Remote Sensing Network (CARSNET), continuous measurements using

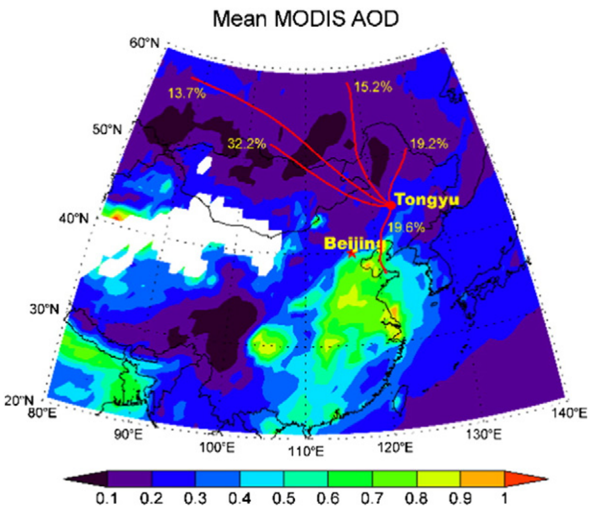

Fig. 1. Spatial distribution of the mean MODIS (aboard NASA's Aqua satellite) AOD at 550 nm from March 2010 to February 2014. The clusters of the 3-day backward trajectories ended at Tongyu (500 m above ground level) are overlaid.