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Clear-sky aerosol optical depth over East China estimated from visibility measurements and chemical transport modeling

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HIGHLIGHTS

- We use chemical transport modeling to improve conversion from visibility to AOD.
- We use MODIS and three ground AOD networks to validate visibility-inferred AOD.
- Seasonal and daytime variations of visibility-inferred AOD agree with MODIS AOD.
- Our visibility-based AOD inference can be used for multi-decadal aerosol studies.

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ABSTRACT

Horizontal visibility measured at ground meteorological stations provides an under-exploited source of information for studying the interdecadal variation of aerosols and their climatic impacts. Here we propose to use a 3-hourly visibility dataset to infer aerosol optical depth (AOD) over East China, using the nested GEOS-Chem chemical transport model to interpret the spatiotemporally varying relations between columnar and near-surface aerosols. Our analysis is focused in 2006 under cloud-free conditions. We evaluate the visibility-inferred AOD using MODIS/Terra and MODIS/Aqua AOD datasets, after validating MODIS data against three ground AOD measurement networks (AERONET, CARSNET and CSHNET). We find that the two MODIS datasets agree with ground-based AOD measurements, with negative mean biases of 0.05–0.08 and Reduced Major Axis regression slopes around unity. Visibility-inferred AOD roughly capture the general spatiotemporal patterns of the two MODIS datasets with negligible mean differences. The inferred AOD reproduce the seasonal variability (correlation exceeds 0.9) and the slight AOD growth from the late morning to early afternoon shown in the MODIS datasets, suggesting the validity of our AOD inference method. Future research will extend the visibility-based AOD inference to study the long-term variability of AOD.

1. Introduction

Climate forcings of aerosols are among the most uncertain aspects in climate change studies. Due to their relatively short lifetimes, aerosols undergo significant spatial and temporal variability, and are highly dependent on emissions, atmospheric formation, transport, and removal processes. The spatiotemporal variability also means that a large amount of measurements with good coverage in space and time are required to constrain their climatic impacts. Such measurements are rare before the 21st century, especially over developing countries like China. Previous studies have suggested that aerosols may have significantly affected surface air temperature (Qian and Giorgi, 2000) and precipitation (Qian et al., 2009) over various parts of China. A reliable dataset for historical aerosols would provide additional insight into these impacts.

Near-surface horizontal visibility has been measured routinely at many ground meteorological stations for many decades. Given

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the impairment of light by aerosols, visibility measurements can be used to infer aerosol optical effects after constraining the effects of non-aerosol factors like air molecules and hydrometeors (Griffing, 1980; Husar et al., 2000; Qian and Giorgi, 2000; Doyle and Dorling, 2002; Vautard et al., 2009; Wang et al., 2012). Previous studies have attempted to convert daily mean or early afternoon visibility to aerosol optical depth (AOD), a key optical characteristic of aerosols in the whole atmospheric column (Qiu and Lin, 2001; Chen et al., 2009b; Wang et al., 2009; Qin et al., 2010). In converting visibility to AOD, these studies have normally assumed an exponential decrease of aerosols with height, with a scale height of 0.8–1.2 km that depends linearly and weakly on visibility (Elterman, 1970). Qiu and Lin (2001) proposed a correction on the vertical profile based on near-surface water vapor pressure. Nonetheless, the simplified conversion approach cannot fully account for the large variability with space and time in the aerosol vertical profile (van Donkelaar et al., 2013; Yang et al., 2013). For example, the vertical shape of aerosols are often not exponential (Liu et al., 2011), and in the downwind regions the free tropospheric aerosols play a much more important role than suggested by the exponential profile (Ford and Heald, 2012). There is also significant variability in vertical mixing in the planetary boundary layer (PBL), with the PBL height varying diurnally and day-to-day by up to an order of magnitude (Lin et al., 2008, 2012; Yang et al., 2013).

In this study, we propose to use a 3-hourly visibility dataset for AOD inference over East China (see Fig. 1 for domain definition). To relate near-surface to columnar aerosols, we employ the vertical profiles of aerosols simulated by the nested GEOS-Chem chemical transport model (CTM). Driven by assimilated meteorology, the model accounts for the horizontal and temporal (hourly, daily and seasonal) variations of aerosol profiles. The model profiles have been used to convert satellite AOD data to near-surface $PM_{2.5}$ mass concentrations (van Donkelaar et al., 2010, 2013) and visibility (Kessner et al., 2013). Similar modeling approaches have been adopted for studying trace gases (Lamsal et al., 2008; Lin et al., 2010). In addition, the use of 3-hourly data allows for an analysis of AOD variability during the daytime, an important aspect for the climatic impacts of aerosols. Although the diurnal variation of AOD is likely small on the annual and global scale (Kaufman et al., 2000; Ichoku et al., 2005), the range of variation depends on season, the magnitude of AOD, and the contribution of anthropogenic sources (Kaufman et al., 2000; Wang et al., 2010).

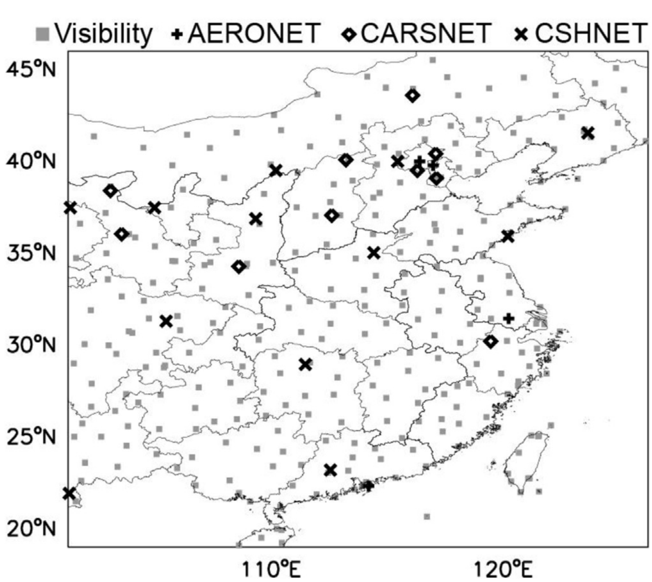

Fig. 1. Stations of visibility measurements and three ground AOD networks over East China.

Visibility-inferred AOD are subject to errors in visibility data, influences by non-aerosol factors, and assumptions in the conversion process from visibility to AOD. We thus evaluate the inferred data using independent AOD data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites and from three ground networks including the AErosol RObotic NETwork (AERONET), the China Aerosol Remote Sensing Network (CARSNET), and the Chinese Sun Hazemeter Network (CSHNET) (see Fig. 1 for locations of the individual stations). Considering that ground stations for AOD measurements are not collocated with stations for visibility observations and that there are much fewer AOD stations, we use ground-based AOD measurements to validate MODIS data and then use MODIS data to evaluate visibility-inferred AOD. Such 'transfer evaluation' maximizes the use of ground-measured and MODIS AOD data. Our analysis is focused in 2006 under cloud-free conditions, concerning the measurement conditions for MODIS and ground AOD networks as well as the data availability in CARSNET and CSHNET (both available for 2006).

Section 2 presents AOD data from MODIS and ground networks, visibility data, GEOS-Chem simulations, and the method to converting visibility to AOD. Section 3 compares MODIS AOD to those from the ground networks. Section 4 evaluates visibility-inferred AOD using MODIS AOD data, focusing on the spatial, seasonal, and daytime hourly variations. Section 5 summarizes the paper.

2. Data, modeling and methodology

2.1. AOD measurements from three ground networks

Fig. 1 shows the distribution of three ground networks over East China. AERONET is a world-renowned remote sensing aerosol monitoring network (Holben et al., 1998). It has been used previously to provide aerosol optical properties (Liu et al., 2007) for the derivation and/or evaluation of satellite remote sensing or atmospheric modeling of aerosols (Mi et al., 2007; van Donkelaar et al., 2013; Lin et al., 2014). However, AERONET includes few sites in China with continuous aerosol measurements, affecting its regional representativeness in various applications. The network provides level-2 (quality-assured) AOD data at the wavelengths of 440 nm, 675 nm, 870 nm and 1020 nm; these data have been subject to both automatic and manual cloud screening. In this study, AOD data at 550 nm at four stations are derived from values at 440 nm using the accompanying Ångström exponent data for 440–675 nm.

Operated by the China Meteorological Administration since 2002, CARSNET is the Chinese version of AERONET designed for studying aerosol optical properties in different areas of China (Che et al., 2009). The network uses the same CE-318 sun photometers as in AERONET. The CARSNET instruments undergo the Langley calibration at the Izana Observatory (INM, Spain), following the protocol used by AERONET. An instrument inter-comparison calibration is also conducted at the Chinese Academy of Meteorological Sciences (CAMS) site (Che et al., 2009, 2013). In addition, sphere calibration is performed every year to ensure the accuracy of the sky irradiance measurement (Tao et al., 2013). CARSNET provides both level 1.0 (raw AOD without cloud screening) and level-1.5 AOD (cloud-screened AOD based on the work of (Smirnov et al. (2000)) products using the ASTPwin software offered by Cimel Ltd. Co. AOD data are available at 440 nm, 670 nm, 870 nm and 1020 nm, together with the Ångström exponent calculated from AOD values at 440 nm and 870 nm. The CARSNET level-1.5 data at the CMAS site agree with the AERONET/PHOTONS level-1.5 data (Che et al., 2009; Pan et al., 2010). The CARSNET dataset