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Analysis of water vapor effects on aerosol properties and direct radiative forcing in China

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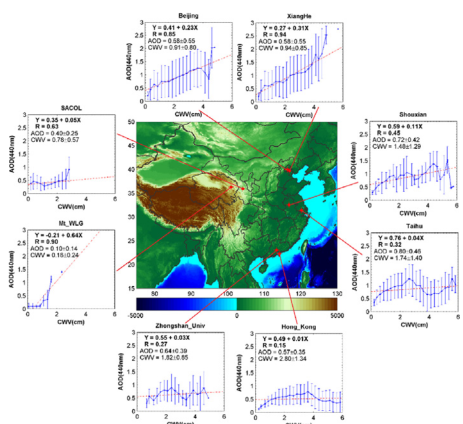
HIGHLIGHTS

- Aerosol properties affected by column water vapor is studied by using AERONET data.
- Impact of water vapor on aerosol properties in China shows obvious spatial variations.
- The mix-small aerosol type is dominated in the high column water vapor air.
- Water vapor weakens aerosol radiative effect at the bottom of the atmosphere.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of column water vapor (CWV) on aerosol optical properties, radiative effects and classification are studied by using aerosol and CWV data from eight Aerosol Robotic Network (AERONET) sites in China: Beijing, XiangHe, Shouxian, Taihu, Hong_Kong, Zhongshan_Univ, SACOL, and Mt_WLG, which represents 5 distinct aerosol climatologies in China. Contrast in correlations between aerosol optical depth (AOD) and CWV is found. High correlation coefficient (R) ranging from 0.63–0.94 is observed at Beijing and XiangHe (North China Plain), SACOL (Northwest China) and Mt_WLG (the Tibetan Plateau). R values at stations in the Middle-East China (Shouxian and Taihu) are within 0.32–0.45. AOD shows poor correlation to CWV in Southeast China (R at Hong_Kong and Zhongshan_Univ of 0.15 and 0.27). At most sites, the asymmetry (ASYM) of fine-mode aerosol increases with CWV with R larger than ~0.4. Aerosol direct radiative forcing efficiency (ADRFE) at the bottom of the atmosphere (BOA) is affected by CWV, with R >~0.5 over the north and Middle-East China sites. The statistic results show that an increase of CWV by 0.1 cm could result in enhancements of ADREF at the BOA by about 1.1–2.8 W m^{-2} at all the sites except Mt_WLG. The aerosol classification shows that the mix-small aerosol type is always dominated under the high CWV air. The clusters of back-trajectories with relative humidity (RH) from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model indicate that the air mass

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with high RH is often from south and east directions. The influence of CWV on aerosol properties is mainly shown in the properties of fine mode aerosol, which needs to be considered in the study of aerosol radiative forcing and climate effects.

1. Introduction

Atmospheric aerosol has an important impact on climate through aerosol-radiation effect and aerosol-cloud interaction (IPCC, 2013) and on atmospheric quality(Zhang et al., 2015; Xing et al., 2017). The cloud on an area affected by the aerosol is also influenced by atmospheric circulations in other areas, such as the cloud cover in China (Yang et al., 2017a; Yang et al., 2017b; Yang et al., 2010). Thus, the accuracy of aerosol radiative forcing, especially aerosol-cloud interactions, is important for understanding aerosol climate change (Zhu et al., 2017; Li et al., 2017; Li et al., 2018; Li et al., 2015). However, the aerosol climate effect has a relatively large uncertainty because of their highly temporal variability and spatial inhomogeneity of aerosol properties and complex sources (Crutzen et al., 2000; Andreae and Crutzen, 1997). Aerosol hygroscopic growth can affect the aerosol optical, physical and even chemical properties (Malm and Day, 2001; Quinn et al., 2005; Sun et al., 2013), thereby substantially impact aerosol radiative effects.

Ground-based remote sensing of aerosols is one of the important tools in accurately characterizing column-integrated aerosol optical and physical properties (Dubovik et al., 2002). Ground-based network of remote sensing aerosol optical properties using sunphotometer goes back to 1960s in America and Europe (Volz, 1965; Holben et al., 2001 and references therein). The AErosol RObotic NETwork (AERONET) offers a standardization for a ground-based regional to global scale aerosol monitoring and characterization network (Holben et al., 1998). Currently, AERONET has provided long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties over hundreds stations across the world (Eck et al., 1999). AEROENT data are widely used to reveal spatial-variation of aerosol optical properties, to evaluate satellite and model aerosol products, and to study aerosol-cloud interactions (Holben et al., 2001; Kaufman and Koren, 2006; Kahn et al., 2007; Das and Sarin, 2009).

Column water vapor (CWV) can also be derived with uncertainty of about 10% from solar direct radiation at 940 nm observed by standardized sunphotometer of AERONET, which provides an opportunity to study how aerosol properties vary with water vapor content. Our objective of this study is to analyze the effect of CWV on aerosol optical, radiative properties and classification by using 8 AERONET sites in China with all seasons of direct sun measurements and sky inversions. Previous studies on AERONET data showed that aerosol optical properties and radiative effect in China had a large spatial variation (Mai et al., 2018; Garcia et al., 2009; Xia et al., 2008; Xia et al., 2007; Li et al., 2007; Xia et al., 2016; Che et al., 2014; Che et al., 2011). Progresses have also made on aerosol impact on radiative forcing by combing AERNOET and satellite remote sensing products (He et al., 2017; Qin et al., 2018; Koehler et al., 2009). It should be noted that potential impacts of CWV on aerosol properties and aerosol radiative effect in China are still worthy of further study. Our work is the first attempt to use AERONET data to reveal the spatial variation of CWV impact on aerosol optical and radiative properties and aerosol classifications in China.

The organization of this paper is as follows. The site, data and methodology are introduced in Section 2. The results of the influence of CWV on aerosol optical and radiative properties, aerosol classification and aerosol and water vapor source are presented in Section 3. The conclusions and discussion are presented in Section 4.

2. Site, data and methodology

2.1. Site

The 8 sunphotometer sites with all seasons (spring, summer, autumn and winter) of measurements located in China are selected to present different dominant aerosol types and regions. The sites locations are shown in Fig. 1 and Table 1. Taking the predominant aerosol types and the proximity to source areas into account, the 8 stations could present five regions. Beijing and XiangHe sites are located in North China Plain region; Shouxian and Taihu are Middle-East China sites. Hong_Kong and Zhongshan_Univ belong to Southeast China region. SACOL site represents the Northwest China. Mt_WLG is the Tibetan Plateau site. This partition refers to that in (Xia et al., 2016). The data of Hong_Kong are from three AERONET stations, i.e., Hong_Kong_Hok_Tsui, Hong_Kong_PolyU, and Hong_Kong_Sheung.

2.2. Data

The data used in this study were downloaded from AERONET website (http://aeronet.gsfc.nasa.gov). The level 2 data used in this study are observed by CE318 sunphotometer. The CE318 instrument performs direct sun extinction measurements at eight wavelengths ranging from 340 to 1020 nm and sky radiance measurements at four wavelengths, i.e., 440, 675, 870, and 1020 nm. The aerosol optical depth (AOD) data were calculated from the direct sun observations with an accuracy of 0.01 to 0.02 (Holben et al., 1998; Eck et al., 1999). The uncertainty in retrieval of CWV is typically <12% (Holben et al., 1998). The Extinction Angstrom Exponent (EAE) is calculated from the spectral AOD. Similar to EAE, the absorption Angstrom exponent (AAE) is calculated from spectral absorption AOD (AAOD) at 440 nm and 870 nm. AAOD is calculated from AOD and single scattering albedo (SSA). SSA uncertainty is estimated to be less than 0.03 for AOD at 440 nm > 0.4 (Dubovik et al., 2000; Dubovik et al., 2002). For the intermediate particle size range ($0.1 < r < 7$ μm), the retrieval errors of particle volume size distribution do not exceed 10% in the maxima of the size distribution and may increase up to 35% for the points corresponding to the minimum values of dV(r)/dlnr within this size range; for the particles less than 0.1 μm and larger than 7 μm, the accuracy decreases significantly because of the low sensitivity of the aerosol scattering at 440, 675, 870 and 1020 nm to particles in these size ranges (Dubovik and King, 2000; Dubovik et al., 2002). Solar radiation products under different aerosol environments at the bottom of atmosphere (BOA) showed an excellent agreement with surface measurements (García et al., 2008; Li et al., 2010). The data information of the direct sun measurements at each site is shown in Table 2.

2.3. Methodology

Use the data statistics between aerosol properties (including aerosol optical and radiative properties) and CWV to show the influence of CWV on the aerosol properties. The aerosol size distributions at different CWV bins are analyzed to explore the variation of aerosol size distribution with CWV. The aerosol radiation products were calculated by using AERONET inversion code according to the reference (Dubovik and King, 2000; Dubovik et al., 2006). Aerosol direct radiative forcing (ADRF) is derived as the difference in the net solar radiation at the top