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A multidimensional comparison between MODIS and VIIRS AOD in estimating ground-level $PM_{2.5}$ concentrations over a heavily polluted region in China

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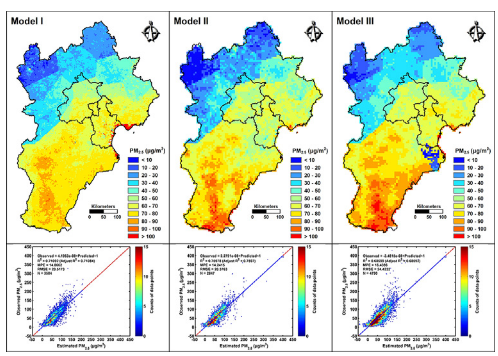
HIGHLIGHTS

- The capacity of MODIS and VIIRS AOD were compared in terms of estimating $PM_{2.5}$.
- The MODIS model explained 71% of the total $PM_{2.5}$ variations.
- The VIIRS model with high-quality AOD explained 76% of the total $PM_{2.5}$ variations.
- The VIIRS models are capable of capturing high $PM_{2.5}$ concentrations.
- The practice of using medium-quality VIIRS AOD is meaningful.

GRAPHICAL ABSTRACT



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ABSTRACT

Satellite-derived aerosol optical depth (AOD) has been proven effective for estimating ground-level particles with an aerodynamic diameter <2.5 μm ($PM_{2.5}$) concentrations. Using a time fixed effects regression model, we compared the capacity of two AOD sources, Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS), to estimate ground-level $PM_{2.5}$ concentrations over a heavily polluted region in China. Regarding high-quality AOD data, the results show that the VIIRS model performs better than the MODIS model with respect to all model accuracy evaluation indexes (e.g., the coefficient of determination, R^2, of the VIIRS and MODIS models are 0.76 and 0.71 during model fitting and 0.72 and 0.66 in cross validation, respectively), the potential for capturing high $PM_{2.5}$ concentrations, and the precision of annual and seasonal $PM_{2.5}$ estimates. However, the spatiotemporal coverage of the high-quality VIIRS AOD is inferior to that of the MODIS AOD. We attempted to include medium-quality VIIRS AOD data to eliminate this, while exploring its influence on the performance of the VIIRS model. The results show that it improves the spatiotemporal coverage of the VIIRS AOD dramatically especially in winter, although a decline in model accuracy occurred. Compared to the MODIS model, the VIIRS model with both high-quality and medium-quality AOD data performs comparably or even better with respect to some model accuracy evaluation indexes (e.g., the model overfitting degree of the VIIRS and MODIS models are 7.46% and 5.82%, respectively), the potential for capturing high $PM_{2.5}$ concentrations, and the precision of annual and seasonal $PM_{2.5}$ estimates. Nevertheless, the VIIRS models

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did not perform as well as the MODIS model in summer. This study reveals the advantages and disadvantages of the MODIS and VIIRS AOD in simulating ground-level $PM_{2.5}$ concentrations, promoting research on satellite-based $PM_{2.5}$ estimates.

1. Introduction

Numerous epidemiological studies have indicated that long-term exposure to particles with an aerodynamic diameter <2.5 μm ($PM_{2.5}$) is associated with various adverse health outcomes (Dominici et al., 2006; Pope et al., 2002; Pope and Dockery, 2006). With rapid urbanization and industrialization, China has become one of the worst regions with respect to fine particle pollution worldwide (Boys et al., 2014; van Donkelaar et al., 2015; van Donkelaar et al., 2016; van Donkelaar et al., 2010). Consequently, national $PM_{2.5}$-related deaths from stroke, ischemic heart disease, lung cancer, etc. have increased dramatically in the past decades (Liu et al., 2016; Wu et al., 2017).

Both epidemiological studies and environmental management efforts benefit from the estimation of spatially fine $PM_{2.5}$ concentrations with high accuracy, resolution, and spatiotemporal coverage. In contrast to limited, costly ground monitoring sites with an uneven spatial coverage in China, satellite remote sensing technology has the potential to achieve such estimations due to its high resolution and spatiotemporal coverage. It is a new and effective tool that has been developed rapidly in recent years (Hoff and Christopher, 2009).

Aerosol optical depth (AOD) is the most commonly used remote sensing parameter in satellite-based $PM_{2.5}$ estimation models, which is defined as the integral of the light extinction caused by aerosol optical absorption and scattering in an atmospheric column and has been proven to correlate with ground-level $PM_{2.5}$ concentrations (Engel-Cox et al., 2004; Hu et al., 2014; Wang and Christopher, 2003). A series of AOD products derived from satellite sensors have been adopted to estimate ground-level $PM_{2.5}$ concentrations. These include AOD products from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Hu et al., 2013; Lee et al., 2011; Ma et al., 2016a; Ma et al., 2016b; Song et al., 2014), Multiangle Imaging SpectroRadiometer (MISR) (Liu et al., 2007; Liu et al., 2005; You et al., 2015), Visible Infrared Imaging Radiometer Suite (VIIRS) (Schliep et al., 2015; Wu et al., 2016), Geostationary Operational Environmental Satellite (GOES) (Liu et al., 2009), and Geostationary Ocean Color Imager (GOCI) (Xu et al., 2015).

Among the above-mentioned AOD products, MODIS AOD has been applied mostly due to its long time series of archived data (Chu et al., 2016). However, MODIS is already working beyond its expected operation period and is expected to cease transmitting data in the future. The VIIRS was designed and launched to address this. As a next-generation polar-orbiting operational environmental sensor with the capability for global aerosol observations, VIIRS aerosol retrieval is expected continue the decade-long successful aerosol retrieval of MODIS for scientific research and applications (Liu et al., 2014; Meng et al., 2015). Although some studies have shown that AOD products from the MODIS and VIIRS are both suitable for estimating ground-level $PM_{2.5}$ concentrations, few studies have compared their capacities. Such comparative studies are important for providing meaningful indications on the respective strengths of MODIS and VIIRS AOD, as well as offering helpful suggestions for improving the new VIIRS.

Therefore, the objective of this study is to compare the capacity of the MODIS and VIIRS AOD in estimating ground-level $PM_{2.5}$ concentrations over a heavily polluted region in China. To this end, we collected 3-km MODIS AOD and 6-km VIIRS AOD from the MODIS Collection 6 (C6) and the VIIRS Environmental Data Record (EDR), respectively. Subsequently, we established several separate satellite-based statistical $PM_{2.5}$ estimation models, one MODIS model and two VIIRS models, using MODIS and VIIRS AOD, respectively, as the main predicator, as well as several auxiliary variables. Next, we compared the capacities of the MODIS and VIIRS models from a multidimensional perspective. Finally, we determined whether the MODIS and VIIRS AOD differ significantly with respect to estimating ground-level $PM_{2.5}$ concentrations over a heavily polluted region in China and offered constructive suggestions on future applications of satellite-derived AOD.

2. Data and methods

2.1. Study area

We used the Beijing-Tianjin-Hebei region as the study area. It is located in Northern China, and includes the entire Beijing municipality, Tianjin municipality, and Hebei province. Due to the long history of industrial development and urban expansion, this region is heavily polluted and faces a greater health burden than other regions in China (Liu et al., 2016). From April 2014 to April 2015, half of the ten cities most affected by haze in China were located in this region, with a maximum annual $PM_{2.5}$ concentration of 118.08 μg/m^3 in Baoding, Hebei (Zhang and Cao, 2015). As the capital area in China, the fine particulate pollution in this region has attracted increasing attention from scholars, the government, and inhabitants. A total of 104 $PM_{2.5}$ monitors and 25 weather stations are distributed throughout this region (Fig. 1). The southeastern area is characterized by a lower terrain and concentration of main human activities.

2.2. Data collection

Ground-level $PM_{2.5}$ data were downloaded from the official website of the China Environmental Monitoring Center (CEMC) and Beijing Municipal Environmental Monitoring Center (BJMEMC). The data were measured using the tapered element oscillating microbalance method (TEOM) or the beta-attenuation method, which are automatic online monitoring methods stipulated by the new ambient air quality standards, and were processed using data quality calibration and control (HJ618-2011, 2011). The temporal resolution of the ground-level $PM_{2.5}$ measurements was 1 h; we used the daily average as the dependent variable.

The MODIS is an important sensor installed on the Terra and Aqua satellites (Remer et al., 2005) of the Earth Observing System (EOS) operated by the National Aeronautics and Space Administration (NASA). The MODIS AOD includes two types of AOD algorithms, the dark target (DT) and deep blue (DB) AOD algorithms. In the newest C6 collection, the MODIS team firstly released 3-km DT AOD products (Remer et al., 2013). We obtained the 3-km MODIS AOD data from the Terra and Aqua satellites from the Level-1 and Atmospheric Archive & Distribution System (LAADS) operated by NASA (code: MOD04_3K, MYD04_3K). The VIIRS is a key sensor onboard the Suomi National Polar-orbiting Partnership (Suomi-NPP) Satellite. It provides two types of AOD products, the intermediate product (IP) AOD and the EDR AOD, with spatial resolutions of 750 m and 6 km (Jackson et al., 2013), respectively. Both can be applied and explored when estimating ground-level $PM_{2.5}$ concentrations. In this study, we mainly aimed to compare the capacities of the 3-km MODIS AOD and 6-km VIIRS AOD to estimate ground-level $PM_{2.5}$ concentrations. Therefore, we collected the EDR AOD (code: VIIRS_EDR) from the Comprehensive Large Array-data Stewardship System (CLASS) operated by the National Oceanic and Atmospheric Administration (NOAA).

The AOD is the total integral of the light extinction caused by aerosol optical absorption and scattering in an atmospheric column. Its