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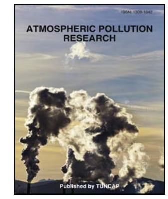

Investigation of air quality over the largest city in central China using high resolution satellite derived aerosol optical depth data

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ABSTRACT

Urban air pollution in China has gained unprecedented attention under the background of high concentration of particulate matter and increasing haze frequency in recent years. In this study, utilizing the high resolution Aerosol Optical Depth (AOD) dataset derived from Gaofen-1 (GF-1) satellite during 2013–2016, we provide a new insight into the air quality over Wuhan, the largest city in central China. Local AOD (LAOD) was introduced to indicate the aerosol loading from local sources. Annual LAOD was found to increase with urban cover in the district scale, which revealed the potential positive feedback between urbanization and regional air pollution. The seasonal pattern of LAOD was consistent with $PM_{2.5}$, both presenting a seasonality of highest in winter and lowest in summer. By locating the highly polluted regions from LAOD map, our research highlighted the impact of anthropogenic aerosol loading (especially from industrial parks) on the regional air quality. Noticing the concentrated distribution of anthropogenic aerosol loading over urban areas, we further defined the urban-induced AOD to quantify the urban aerosol effect by comparing LAOD between urban areas and other land types. Consistent with the change trend of $PM_{2.5}$, annual urban-induced AOD also presented a slight downward trend, which was a reasonable response to the stricter environment policies adopted by local government in recent years. Though carried out as a case study over Wuhan in central China, we believe that the findings presented here would promote the understanding of air pollution in most mega cities of China.

1. Introduction

Atmospheric aerosols, generated from natural sources (e.g. sea spray, dust storm, and forest fire) and anthropogenic sources (e.g. fossil fuel, biomass burning, traffic and industrial emission), play a crucial role in climate change, radiative forcing, visibility and air quality (Haywood and Boucher, 2000; Kaufman et al., 2002; Wang et al., 2009; Huang et al., 2014; Stocker, 2014). However, owing to a wide spatial and temporal variability in aerosol mass concentration, aerosol type and aerosol composition, atmospheric aerosol remains to be a dominant source of uncertainty in the understanding of global climate system (Mishchenko et al., 2007; Stocker, 2014).

A convenient and efficient way to quantify the characteristics of atmospheric aerosol spatially and temporally is satellite remote sensing (Yang et al., 2014). Although there still exist a certain degree of uncertainty, a number of satellite-based instruments, such as Moderate Resolution Imaging Spectrometer (MODIS) (Hsu et al., 2013; Levy et al., 2013), Advanced Very High Resolution Radiometer (AVHRR) (Mishchenko et al., 2003), Total Ozone Mapping Spectrometer (TOMS) (Torres et al., 2002), Multi-angle Imaging Spectro-Radiometer (MISR) (Kahn et al., 2010), and Visible Infrared Imaging Radiometer Suite (VIIRS) (Jackson et al., 2013), have provided massive aerosol related products at global scale over the past few decades. One significant aerosol optical property derived from satellite measurements is Aerosol Optical Depth (AOD), which is used to indicate the degree of light attenuation by aerosols through the observation path of atmosphere.

Satellite derived AOD products have been widely used in the global/regional air quality study, including analyzing the formation of haze pollution (Tao et al., 2012, 2016), evaluating anthropogenic aerosol loading (Ginoux et al., 2010; Hao et al., 2011), and estimating the spatiotemporal distribution of $PM_{2.5}$ (Sorekhamer et al., 2013; Van Donkelaar et al., 2016). Nevertheless, most of the frequently-used AOD

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products at global scale (e.g. MODIS, AVHRR, MISR and VIIRS) have a spatial resolution ranging from a few kilometers to several tens of kilometers, which are too coarse to the urban scale applications. Take Wuhan, the largest city in central China for example, there only have 15 × 15 pixels at most covering the city for the commonly used MODIS AOD product at 10 km resolution. It is obviously insufficient to capture the spatial variety of air pollution throughout the city. Although finer resolution products such as the MODIS AOD at 3 km (Remer et al., 2013) and VIIRS AOD at 750 m (Jackson et al., 2013) have also been released, some significant problems, including larger uncertainty in the algorithm accuracy and difficulties in the retrieval over urban surfaces, limit their applications in the urban scale study (Munchak et al., 2013; Huang et al., 2016). In addition, there have been many studies which utilized the 1 km resolution MODIS AOD derived from Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm to investigate the spatial distribution, scale and variety of aerosol particle concentration at regional scale (Chudnovsky et al., 2013; Alexeeff et al., 2015; Just et al., 2015; Lee et al., 2016; Sever et al., 2017). Though not available over the entire China at present, the high resolution MAIAC AOD data are beginning to be applied in estimating ground PM2.5 concentration over mega cities of China including Beijing and Shanghai (Liang et al., 2017; Xiao et al., 2017). With the rapid growth of urbanization and industrialization in recent years, air pollution has become an increasingly serious environmental problem in China (Song et al., 2017). High $PM_{2.5}$ concentration and heavy haze pollution were reported to frequently occur in mega cities of China (Tao et al., 2012; Rohde and Muller, 2015). To better understand the air pollution in urban scale, high resolution AOD products covering all land surface types (especially urban areas) are in strong demand all the time.

In this paper, we provide a fresh perspective on the air quality over Wuhan city by taking advantage of a high resolution AOD dataset from our previous work (Sun et al., 2017). The AOD dataset, derived from Wide-Field-of-View (WFV) Camera data onboard Chinese Gaofen-1 (GF-1) satellite, has a spatial resolution of 160 m × 160 m and a re-visiting period of 4 days. GF-1 WFV AOD covers all land surfaces including urban areas in Wuhan, and shows good consistency with MODIS AOD product and ground measurements (Sun et al., 2017). These advantages make it suitable to be applied in the evaluation of air quality over Wuhan. Utilizing the GF-1 WFV AOD dataset from 2013 to 2016, we analyzed the spatial distribution characteristics of AOD over Wuhan, including the AOD map on clean and polluted days, the annual and seasonal variation, and the highly polluted regions. The impacts of land cover types and road density on the spatial distribution of AOD over Wuhan were also discussed. These findings presented in the paper would promote the understanding of air quality in city scale.

2. Study area

Wuhan (113°41′E–115°05′E, 29°58′N–31°22′N), situated on the middle-lower Yangtze Plain and eastern Jianghan Plain, is provincial capital of Hubei province and the largest city in central China, with a population of more than ten million and a covering area of approximately 8594 km^2 (Fig. 1). The city is divided into thirteen districts, which are Caidian, Qiaokou, Dongxihu, Hannan, Hanyang, Hongshan, Huangpi, Jiangan, Jianghan, Jiangxia, Qingshan, Wuchang, and Xinzhou respectively. Seven districts located in the central section (Qiaokou, Hanyang, Hongshan, Jiangan, Jianghan, Qingshan, and Wuchang) constitute the core urban region of Wuhan city (highlighted by red line in Fig. 1). The air pollution over Wuhan has become increasingly serious under the background of rapid development of urbanization and industrialization in recent years. The annual mean AOD at 500 nm was found to be relatively high (up to 1.0) over Wuhan in the last few years (Wang et al., 2015). Wuhan was also identified as a significant region with high aerosol loading in some national scale studies (He et al., 2016b; Sun and Chen, 2017).

3. Material and methods

3.1. GF-1 WFV AOD data

The AOD data used in the study were obtained from our previous work, in which we developed an operational AOD retrieval algorithm for the WFV camera data onboard GF-1 satellite (Sun et al., 2017). The time range of GF-1 WFV AOD is from July 2013 to December 2016, corresponding to all the valid GF-1 satellite data up to 2016. The temporal distribution of valid GF-1 WFV AOD retrievals from 2013 to 2016 is shown in Table 1. There are about 40 days with valid AOD retrievals per year in average. The GF-1 WFV AOD was retrieved by an improved deep blue method similar to the algorithm adopted by MODIS AOD product, which made it possible to cover all land surfaces including urban areas over Wuhan, as well as high spatial resolution (160 m × 160 m) and temporal resolution (4 days). The proposed algorithm utilized the high reflectivity by cloud and high contrast between clouds and the underlying surface to screen clouds. The detailed criterion is: if $\rho_{red}^{TOA} > 0.2$ and $\rho_{red}^{TOA} - \rho_{red}^{surface} > 0.1$ then mask. Generally, the method shows a reasonable performance in the cloud mask of GF-1 WFV data. Although in some cases the looser thresholds may result in some extremely high AOD values which actually are retained clouds, the impact of clouds can be minimized in the statistical analysis. Validation results showed that GF-1 WFV AOD had a good consistency with spatio-temporally collocated MODIS AOD (R^2 = 0.66; RMSE = 0.27) and in-situ sun photometer measurements (R^2 = 0.80; RMSE = 0.25). It demonstrates the availability of GF-1 WFV AOD in the evaluation of air quality over Wuhan.

3.2. GF-1 WFV classification data

To analyze the GF-1 WFV AOD over different land use types in Wuhan, a land use map derived from GF-1 WFV imagery was used in the study (Fig. S1). The GF-1 WFV imagery at 16 m resolution was classified using eCognition software, an object-oriented image classification tool designed for high resolution satellite data. The imagery was classified as five types: farmland, urban area, forest, barren land, and water, and they accounted for 24.0%, 23.3%, 20.4%, 17.2%, and 15.0% of the total area respectively. The overall accuracy of the classified results reached to 93.45% in the validation.

3.3. Ground-measured $PM_{2.5}$ data

Hourly ground-measured $PM_{2.5}$ data at 10 monitoring sites in Wuhan from 2013 to 2016 were collected from China Environmental Monitoring Center (CEMC; http://www.cnemc.cn). The ground level $PM_{2.5}$ concentrations were acquired by Tapered Element Oscillating Microbalance (TEOM) method with an accuracy of ± 1.50 μg/m^3 (Wang et al., 2010). Daily average $PM_{2.5}$ were first calculated based on the hourly data from all sites, then annual and seasonal mean $PM_{2.5}$ over Wuhan were obtained to validate the results derived from satellite data.

3.4. Roadway data

The roadway data over Wuhan were obtained from OpenStreetMap in shapefile type (downloaded September 21, 2016; http://www.openstreetmap.org/). The spatial distribution of the roads over Wuhan can be seen in Fig. S2. To explore the relationship between road density and AOD, total road density was calculated using the line density tool in ArcGIS spatial analyst toolbox at the same spatial resolution with GF-1 WFV AOD data.

3.5. Definition of local AOD

As satellite derived AOD is an indicator of total aerosol loading from