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A new method of satellite-based haze aerosol monitoring over the North China Plain and a comparison with MODIS Collection 6 aerosol products

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ABSTRACT

With worldwide urbanization, hazy weather has been increasingly frequent, especially in the North China Plain. However, haze aerosol monitoring remains a challenge. In this paper, MODerate resolution Imaging Spectroradiometer (MODIS) measurements were used to develop an enhanced haze aerosol retrieval algorithm (EHARA). This method can work not only on hazy days but also on normal weather days. Based on 12-year (2002–2014) Aerosol Robotic Network (AERONET) aerosol property data, empirical single scattering albedo (SSA) and asymmetry factor (AF) values were chosen to assist haze aerosol retrieval. For validation, EHARA aerosol optical thickness (AOT) values, along with MODIS Collection 6 (C6) dark-pixel and deep blue aerosol products, were compared with AERONET data. The results show that the EHARA can achieve greater AOT spatial coverage under hazy conditions with a high accuracy (73% within error range) and work a higher resolution (1-km). Additionally, this paper presents a comprehensive discussion of the differences between and limitations of the EHARA and the MODIS C6 DT land algorithms.

1. Introduction

Haze is defined as a weather phenomenon in which air has a relative humidity of ≤80% and atmospheric visibility of <10 km (World Meteorological Organization, WMO). Thick haze is detrimental to the environment and public health (Hoek et al., 2010). In recent years, due to rapid worldwide urbanization, haze has become a serious problem in many countries. In China in particular, increased industrialization and fossil-fuel consumption have caused serious particulate-matter (PM) pollution, resulting in frequent haze. The increase in haze has been associated with mortality and morbidity from respiratory diseases and cardiovascular problems (Ram et al., 2014). Haze can contain high concentrations of heavy metals and PM, which are thought to be the most harmful pollution components (Huang et al., 2012). Thus, mitigation of haze pollution has become a crucial challenge for environmental management agencies in urban areas. In this context, the sources and spatial distribution of haze are of particular concern.

Many studies have been performed to analyze the physical and chemical characteristics of haze (Che et al., 2009; Huang et al., 2011; Sun et al., 2006). However, most studies have been based on ground and point measurements, which lack spatial coverage and may not elucidate the sources contributing to the formation of haze in widespread areas (Tao et al., 2012). To overcome this limitation, satellite remote sensing can be used to monitor and describe the spatial variability of regional haze. In recent studies, the Moderate Resolution Imaging Spectroradiometer (MODIS) has been widely applied in the field of haze analysis due to its large spatial and temporal coverage (Lee et al., 2006a; Lee et al., 2006b; Noh et al., 2009; Tao et al., 2014). For example, Tao et al. (2012) provided large-scale and long-term insights into regional haze over the North China Plain of Eastern China using MODIS data, and Han et al. (2013) proposed an enhanced dust index for Asian dust detection.

Using satellite imagery to monitor haze aerosol optical thickness is also an effective way to assess air pollution levels. The MODIS atmosphere Level 2 aerosol product has been widely used and shown a high accuracy. It has three aerosol retrieval algorithms: dark-target (DT) land algorithm, DT ocean algorithm and deep-blue (DB) algorithm. However, the aerosol model on hazy days is very different from that on less-polluted days, the default aerosol model in the DT land algorithm of MODIS Aerosol Optical Thickness (AOT) products may be not suitable. In addition, hazy weather conditions are always accompanied by a thick aerosol layer, which causes uncertainty in the relationship between the visible (VIS) and the short-wave infrared (SWIR) bands, but it is still used in the DT land algorithm of the MODIS AOT products. Lee et al. (2006b) also found that using the MODIS SWIR-to-VIS ratio to determine surface reflectance over Northeast Asia could lead to errors in aerosol retrieval. In order to monitor haze distribution, Li et al. (2013) presented an AOT retrieval method for heavy haze events based on a

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lookup table (LUT) method; however, the maximum retrieval of AOT by this method is 3.0, while in Beijing the AOT will be more than 5.0 on some hazy days, such as on July 6, 2014. Thus, accurate AOT retrieval is still a difficult task under hazy weather conditions. In addition, although many current aerosol retrievals make use of the LUT, it is time consuming when building it (Li et al., 2005; Wong et al., 2011; Zha et al., 2011). Tang et al. (2005) used the synergy of Terra and Aqua MODIS data (SYNTEM) to obtain AOTs in China without an LUT, but the results tended to be poor when there was an obvious difference in weather conditions between two observation passes. Luo et al. (2015) proposed an improved aerosol retrieval algorithm with fast calculation and reliable outcomes; however, the method is based on Landsat images and intended for urban-scale studies, and is not suitable for haze aerosol monitoring of larger areas.

The purpose of this study is to develop a new algorithm to obtain aerosol conditions; it includes haze identification, retrieval of AOT not only on hazy days but also in normal weather. A comprehensive discussion of the differences and limitations of this method compared with the C6 DT land algorithm is also presented in this study.

2. Data and methods

2.1. Study area

The North China Plain is the largest alluvial plain in China, with an area of 409,500 km^2, as shown in Fig. 1. The region includes Beijing, Tianjin, and Hebei, whose gross domestic product accounted for 11.3% of China's GDP in 2007. With the development of urbanized construction, the land cover in the North China Plain has changed markedly. Many main roads and residential buildings have been built to accommodate the increase in motor vehicles and in population. Even though the government has made great efforts to improve the environment, urban air pollution problems have become increasingly serious. Particulate matter levels are severe around the cities and continuous air-pollution episodes such as haze events are more frequent than in the past (Li et al., 2013).

2.2. Satellite data

Daytime MODIS TERRA satellite images were acquired (https://ladsweb.nascom.nasa.gov/data/search.html) from December 2013 to June 2015, as shown in Table 1. TERRA is a satellite launched in 1999 that passes from north to south over the study area every morning (ca. 10:30 a.m. local time); with 36 wavebands, it can be used for atmospheric, oceanic, and land studies at both global and local scales.

Collection 6 MODIS aerosol products (C6 MOD04) were obtained for this study, and C6 DT AOT with 10-km and 3-km resolution (Optical_Depth_Land_And_Ocean) were used as a comparison. In addition, MODIS C6 DB AOT with 10-km resolution (Deep_Blue_Aerosol_Optical_Depth_550_land_Best_Estimate) was also obtained for comparison, which was filtered by quality assurance (QA) (Hsu et al., 2013; Sayer et al., 2013). The C6 cloud mask data (Aerosol_Cldmsk_Land_Ocean) were extracted from MOD04 and used for cloud detection in our algorithm.

The MODIS Albedo product (MCD43) was also acquired. It provides data describing both directional hemispherical reflectance (black-sky albedo) and bi-hemispherical reflectance (white-sky albedo). The MCD43A1 Bi-directional Reflection Distribution Function (BRDF)/Albedo Model Parameters Product provides the weighting parameters associated with the Ross Thick–LiSparse Reciprocal BRDF model. These three parameters (fiso, fvol, and fgeo) are provided for each of the MODIS spectral bands. In this study, fiso, fvol, and fgeo in Bands 1 and 3 were collected to calculate surface reflectance.

2.3. Enhanced haze aerosol retrieval algorithm (EHARA)

A new method is described here for haze monitoring and AOT retrieval based on MODIS data. This algorithm is designed for application in large areas characterized by the complex land surfaces of cities or

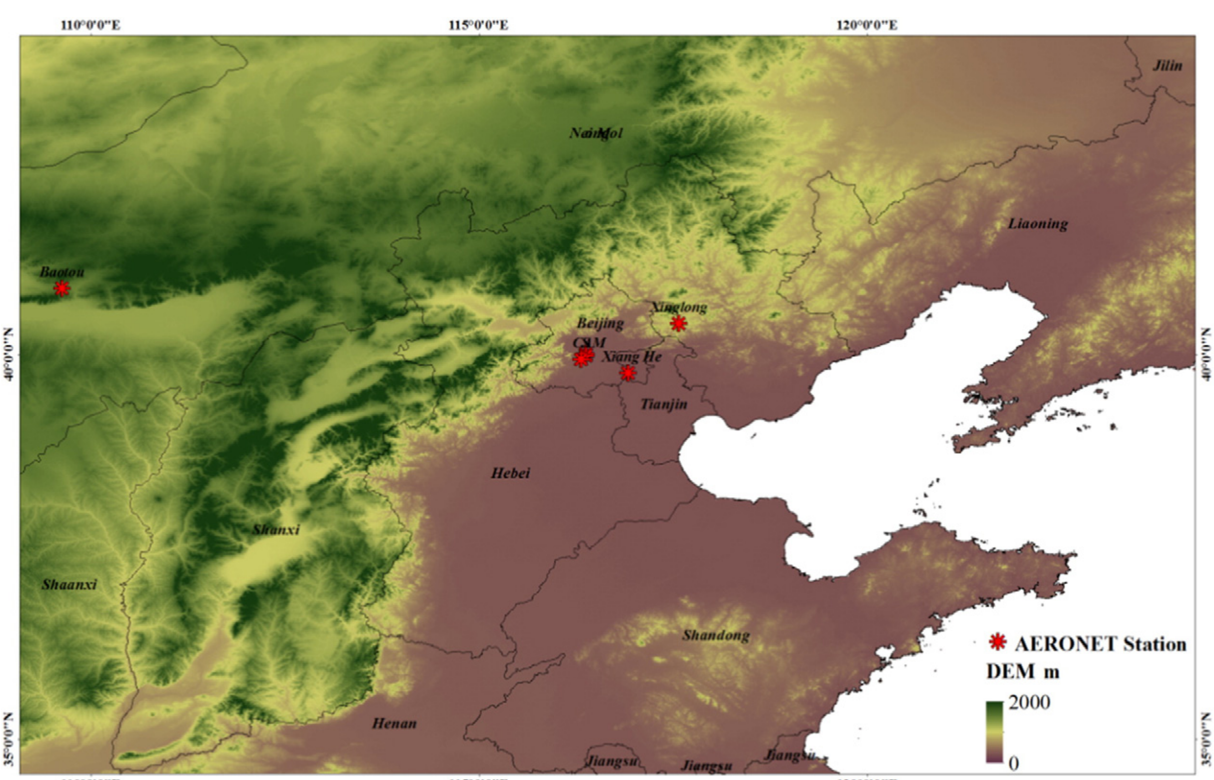

Fig. 1. Study area.