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Improved estimation of aerosol optical depth from MODIS imagery over land surfaces

Shunlin Liang *, Bo Zhong, Hongliang Fang

Department of Geography, University of Maryland, College Park, MD 20742, USA

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Abstract

Estimation of aerosol loadings is of great importance to the studies on global climate changes. The current Moderate-Resolution Imaging Spectroradiometer (MODIS) aerosol estimation algorithm over land is based on the "dark-object" approach, which works only over densely vegetated ("dark") surfaces. In this study, we develop a new aerosol estimation algorithm that uses the temporal signatures from a sequence of MODIS imagery over land surfaces, particularly "bright" surfaces. The estimated aerosol optical depth is validated by Aerosol Robotic Network (AERONET) measurements. Case studies indicate that this algorithm can retrieve aerosol optical depths reasonably well from the winter MODIS imagery at seven sites: four sites in the greater Washington, DC area, USA; Beijing City, China; Banizoumbou, Niger, Africa; and Bratts Lake, Canada. The MODIS aerosol estimation algorithm over land (MOD04), however, does not perform well over these non-vegetated surfaces. This new algorithm has the potential to be used for other satellite images that have similar temporal resolutions.

Keywords: Aerosol; MODIS; Remote sensing; Land surfaces

1. Introduction

Atmospheric aerosol plays a significant role in the Earth's radiation budget through radiative forcing and chemical perturbations. Anthropogenic aerosols are intricately linked to the climate system and the hydrologic cycle. The net effect of aerosols is to cool the climate system by reflecting sunlight (Kaufman et al., 2002). Quantifying the net effect requires accurate information on the global distribution of aerosol properties that have to be estimated from satellite observations. Estimating aerosol properties is also one of the first steps in generating high-level land surface products from satellite observations.

The Moderate-Resolution Imaging Spectroradiometer (MODIS) is one of the sensors in the NASA Earth observing system (EOS) Terra platform launched on December 18, 1999 for imaging in the morning, and the Aqua platform launched on May 4, 2002 for imaging on the afternoon. MODIS has 36 spectral bands spanning from the visible to the thermal-infrared (IR) spectrum. The spatial resolution varies from 250 m (bands 1 and 2), 500 m (bands 3–7), to 1000 m (bands 8–36). The swath width of MODIS is about 2300 km, with the across-track field-of-view angle of 110°. Each MODIS has the global coverage every 2 days, with a 1-day or more frequent repeat at higher latitudes greater than 30° due to orbital convergence. The details of the sensor characterization are available elsewhere (Salomonson et al., 1989).

There is a relatively long history of the quantitative estimation of aerosol optical depth from remotely sensed imagery (Liang, 2004), for example, using multiangular information (Diner et al., 2005; North, 2002), polarization information (Deuze et al., 2001), multispectral information (Kaufman et al., 1997b; Liang & Fang, 2004; Liang et al., 1997; Teillet & Fedosejevs, 1995) and multitemporal information (Christopher et al., 2002; Hauser et al., 2005; Zhang & Christopher, 2001). The MODIS science team (Kaufman et al., 1997a, 1997b; Remer et al., 2005) uses the dark-object method to estimate aerosol optical depth from MODIS imagery over land for climate study. However, its major limitation is its suitability only for densely vegetated ("dark") surfaces. If no dense vegetation canopies are detected in the window of 10 km

* Corresponding author. Tel.: +1 301 405 4556; fax: +1 301 314 9299.
E-mail address: sliang@umd.edu (S. Liang).

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by 10 km, no aerosol retrieval occurs. The recent validation results of the MODIS aerosol optical depth (e.g., Levy et al., 2005; Tripathi et al., 2005) indicate the need for improvement.

There are few alternative algorithms (e.g., Hsu et al., 2004; Tang et al., 2005). For example, Hsu et al. (2004) proposes a new approach to retrieve aerosol properties over bright surfaces using the minimum reflectance determined from $0.1° * 0.1°$ grid. The spatial resolution is not sufficient for atmospheric correction of MODIS imagery at 500 m or 1 km scale. The accuracy of 30% at this scale also needs to be improved. Tang et al. (2005) establishes an empirical relationship between the top-of-atmosphere reflectance and surface reflectance, and MODIS data from two successive orbits are used to solve the nonlinear equation. Any errors resulting from geometric registration and subpixel clouds may significantly affect the solutions. Therefore, further development of new algorithms is critically needed, particularly for bright surfaces.

In this study, we develop a new algorithm for estimating the aerosol optical depths using multi-temporal MODIS data over land surfaces. This algorithm is validated using AERONET measurements. The rest of this paper will start with a brief overview of the official MODIS algorithm, and then describe a new algorithm. Case studies are presented in Section 4 to validate and demonstrate this new algorithm. A short summary and some remaining issues are discussed in the last section.

2. The MODIS algorithm

In the past decade, the MODIS team has developed the "dark-object" method for aerosol estimation (Kaufman et al., 1997a, 1997b; Kaufman et al., 2000). The "dark-object" method is probably the most widely used approach for atmospherically correcting different remotely sensed imagery (Kaufman et al., 1997a; Kaufman et al., 2000; Liang et al., 1997; Popp, 1995; Teillet & Fedosejevs, 1995). The basic assumption is that if the surface is densely vegetated, the middle infrared surface reflectances around 2.1 μm (MODIS band 7) ρ_7 are linearly related to surface reflectances at the blue band (band 3 around 0.49 μm) ρ_3 and the red band (band 1 around 0.66 μm) ρ_1. Since most aerosol sizes are smaller than the middle-IR wavelength, aerosol effects in band 7 are negligible and its surface reflectance (ρ_7) can then be easily estimated. Based on surface measurements, Kaufman et al. (1997b) established the following empirical formulae:

$$\begin{cases} \rho_1/\rho_7 = 0.25 \\ \rho_3/\rho_7 = 0.5 \end{cases} \tag{1}$$

After calculating surface reflectances of bands 3 and 1 (ρ_1, ρ_3) from their linear relationships with band 7 reflectance (ρ_7), aerosol optical depths at bands 1 and 3 can be estimated by using the look-up tables. These look-up tables are pre-calculated for each aerosol models that are pre-defined for a given location and time.

There are two key requirements associated with this method: (1) existence of large homogeneous dense vegetation in the scene; (2) stable empirical relationships of surface reflectance between band 7 and bands 3 and 1. The first requirement precludes the accurate reflectance retrieval of surfaces with non-dense vegetation canopies. To meet the second requirement, dense vegetation canopies have to be distinguished from other dark objects, such as wet soil and water.

If no dense vegetation canopies are detected in the window of 10 km by 10 km, no aerosol retrieval occurs. As a result, the spatial distribution of the aerosol optical depth from the MODIS algorithm (MOD04) has the chessboard-like pattern, where some windows are based on the actual retrievals, and others are filled. MODIS surface reflectance product (MOD09) uses the similar algorithm to derive aerosol optical depth for atmospheric correction. For non-dense vegetation surfaces (e.g., snow/ice, desert, agricultural lands before and after the growing peak), MOD09 products are not accurate because of no aerosol correction with the actual retrieval, which results in large errors in the downstream products, such as snow/desert albedo and canopy leaf area index. After examining the MODIS aerosol optical depth product around the world, it is found that in many cases (mainly off growing season) the MODIS algorithm fails to retrieve aerosol optical depth over land because the surfaces are not covered by dense vegetation canopies. In a particular example, after obtaining 99 MOD04 files from U. S. Geological Service (USGS) EROS Data Center (EDC) over the greater Washington, DC area, centered at Goddard Space Flight Center, after specifying the order for year 2001, there were only 29 actual aerosol retrievals out of 99, which leads to less than 30%.

3. The new algorithm

The new aerosol estimation algorithm over land takes full advantage of MODIS multitemporal observation capability, particularly when we combine observations from both Terra and Aqua platforms. The flow chart of the algorithm is shown in Fig. 1. The central idea of this algorithm is to detect the "clearest" observation during a temporal window for each pixel. If we assume the aerosol optical depths for the "clearest" observations to be known, the aerosol optical depths of other "hazy" observations can be interpolated from the surface reflectance of the "clearest" observations.

We will follow the current MODIS aerosol estimation algorithm (Kaufman et al., 1997a, 1997b; Remer et al., 2005) as much as possible so that we can take full advantage of whatever has been developed for operational applications. The major differences are discussed as follows.

(1) Identifying the "clearest" observations of each pixel and converting their TOA reflectance to surface reflectance. MODIS has acquired data since the year 2000. The multi-temporal observations are used to determine the "clearest" observations. The "clearest" one corresponds to the minimal aerosol contamination, thus, the surface reflectance can be determined with less uncertainty. The idea has been used to determine surface reflectance from other sensors, such as Missions of the Total Ozone Mapping Spectrometer (TOMS) (Hapke, 1984; Herman et al., 2001) and Geostationary Operational Environmental Satellite (GOES) (Christopher et al., 2002; Wang et al., 2003).