Accuracy assessment of Terra-MODIS aerosol optical depth retrievals

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Abstract. Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products have been widely used to address environment and climate change subjects with daily global coverage. Aerosol optical depth (AOD) is retrieved by different algorithms based on the pixel surface, determining between land and ocean. MODIS-Terra and Global Aerosol Robotic Network (AERONET) products can be obtained from the Multi-sensor Aerosol Products Sampling System (MAPSS) for coastal regions during 2000–2010. Using data collected from 83 coastal stations worldwide from AERONET from 2000-2010, accuracy assessments are made for coastal aerosol optical depth (AOD) retrieved from MODIS aboard the Terra satellite. AOD retrieved from MODIS at 0.55μm wavelength has been compared with AERONET derived AOD, because it is reliable with the major wavelength used by many chemistry transport and climate models as well as previous MODIS validation studies. After removing retrievals with quality flags below 1 for Ocean algorithm and below 3 for Land algorithm, The accuracy of AOD retrieved from MODIS Dark Target Ocean algorithms (correlation coefficient R² is 0.844) and a regression equation of τ_M = 0.91·τ_A + 0.02 (where subscripts M and A represent MODIS and AERONET respectively), is the greater than the MODIS Dark Target Land algorithms (correlation coefficient R² is 0.764 and τ_M = 0.95·τ_A + 0.03) and the Deep Blue algorithm (correlation coefficient R² is 0.652 and τ_M = 0.81·τ_A + 0.04). The reasons of the retrieval error in AOD are found to be the various underlying surface reflectance. Therefore, the aerosol models and underlying surface reflectance are the dominant factors which influence the accuracy of MODIS retrieval performance. Generally the MODIS Land algorithm implements better than the Ocean algorithm for coastal sites.

1. Introduction

Aerosols, the suspended liquid, solid particles and small in the atmosphere, are significant ingredients of Earth’s climate system. Between their many roles, they drive the hydrological cycle [10], force the worldwide energy budget [6] and in many concentrations are harmful to human health [14]. Determining aerosol worldwide distribution and changes over time are essential for realizing present and feasible future climate conditions [6]. Towards these aims; NASA has installed a collection of satellites known as the Earth Observation System (EOS) to display a number of main climate properties, including aerosols. one of these EOS-era satellite sensors are the MODerate resolution Imaging Spectroradiometers (MODIS, [17]), which have been flying in polar orbit on Terra since 2000 [17].

This paper focuses on the characterization of MODIS AOD uncertainty over the coastal regions because: (a) The MODIS AOD product over the coastal region is a simple union of the retrievals from algorithms that are planned for either open ocean only or over land only, and neither algorithm has a separated plan to characterize the surface reflectance over the coastal region that is mostly influenced by a water reflectance and sand-water mixture contributed by the underlying seacoast and suspended matter in the coastal ocean; (b) the coastal region is mostly of high significance to its local economic development
through either tourism or serving as a hub for freight transportation [20]. Thus, the evaluation of the MODIS AOD product over the coastal region is decretive for studying the tendency of regional anthropogenic AOD and air pollution.

Several studies have found that the uncertainties in the instantaneous AOD retrievals from satellite sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-Angle Imaging SpectroRadiometer (MISR) are generally within the (pre-launch) expected error (EE) envelope that is often characterized as a linear function of AOD itself. For example, in comparison with world-wide AOD measured from Aerosol Robotic Network (AERONET), MODIS AOD product is shown to have an EE envelope of ±(0.05+0.15AOD_aeronet) over land and ±(0.03+0.05AOD_aeronet) over the ocean ([15], [11], [12], [8]). This paper is designed to address the overall accuracy of MODIS AOD over coastal region with the Dark Target algorithms, over land and ocean ([15]), [11], [12]) and the Deep Blue algorithm over over bright-reflecting land surfaces, such as desert, semiarid, and urban regions ([3], [4]).

2. MODIS and AERONET AOD products

2.1. MODIS Data

MODIS Level 2 Collection 5.1 MOD04 aerosol data from 2 March 2000 through 28 December 2010 are used (http://giovanni.gsfc.nasa.gov/mapss/). The 550 nm wavelength is used for comparison with AERONET because it is consistent with the main wavelength used by many climate transports and chemistry models [9] also prior MODIS validation studies ([11], [12]). MODIS uses quality flags to characterize the accuracy of AOD retrievals. The quality flags range from 3 (high confidence) to 0 (low or no confidence) (Levy et al., 2010). The quality flags are determined to each MODIS AOD retrieval based on the quality and number of pixels used in the AOD algorithms ([15], [12]). Therefore, all MODIS data in this study is filtered by quality flag.

2.2. AERONET Data

AERONET AOD is derived from direct sun photometer measurements in certain or all of the following seven various spectral bands centered at 340, 380, 440, 500, 670, 940 and 1020 nm [2]. AERONET measures the extinction of direct beam solar radiation and applies the Beer–Lambert–Bouguer law to determine AOD [2] with uncertainties on the order of 0.01-0.02 [1]. Only cloud-screened and quality-assured AERONET Level 2 data are used in this study to evaluate the MODIS aerosol product [18].

3. Methodology

MODIS aerosol products in C5.1 are retrieved with two different algorithms, i.e. the Dark Target (DT) ([“DT” ocean and land; ([7], [15]) and the Deep Blue (DB) ([3], [4]).

3.1. Dark Target Algorithm

The MODIS aerosol algorithm is actually two totally autonomous algorithms, one for deriving aerosols over ocean and the second for aerosols over land. Both algorithms were developed and conceived before the Terra launch and are described in depth in [7] and [19]. In the MODIS Dark Target land algorithm, the 500 m spatial resolution reflectance at three bands (470, 650, and 2130 nm), after correction for ozone, water and carbon dioxide, are organized into nominal 10×10 km² boxes corresponding to 20 ×20 or 400 pixels per box. Following the deletion of cloud, snow/ice, and water pixels, the residual pixels are subjected to more process to retrieve AOD with four main steps: (1) recognizing dark pixels whose reflectance at 2130 nm falls in the typical value range of 0.01-0.25 and are about 20% to almost 50% of the corresponding reflectance at 650 nm (red band); (2) parameterizing the surface reflectance at visible (VIS) bands (470 nm and 650 nm) in term of the small wavelength infrared (SWIR, 2130 nm) surface and the corresponding “surface greenness”, the normalized ratio of measured reflectances at 1240 and 2130.
nm channels [11]; (3) selecting the proper aerosol mode and type from a look-up-table, which is the function of geography and season; (4) deriving the optical thickness and mass concentration of the accumulation and coarse mode from the detected radiance. The details of dark target algorithm could be found in [7], [15] and [11].

Figure 1. Map of the location of all coastal AERONET sites

In the MODIS DT ocean algorithm, though the main inversion remains like the process described in [19], the masking of sediments and clouds, the special handling of heavy dust including dust retrievals over glint, and revisals of the look-up table are new. As in the land algorithm, after the ozone, carbon dioxide and water vapor corrections are applied, the primary phase in the ocean algorithm is to organize the reflectance of the six wavelengths used in the process ($\rho_{0.55}$, $\rho_{0.66}$, $\rho_{0.86}$, $\rho_{1.24}$, $\rho_{1.6}$, $\rho_{2.13}$) into nominal 10-km boxes of 20×20 pixels at 500-m resolution. This needs reducing the resolution of the 250-m channels ($\rho_{0.66}$ and $\rho_{0.86}$). The ocean algorithm needs all 400 pixels in the box to be recognized as ocean pixels by the MOD35 mask. This assists to decrease problems presented by shallow water near the coasts. If any land is encountered, the whole box is left for the land algorithm, but quality is reduced for coastal land retrievals.

3.2. Deep Blue Algorithm

The MODIS DT AOD retrieval is based on the relevance between the surface reflectance at SWIR and VIS, which is valid for most vegetated land surfaces but is generally invalid for desert, urban, arid, semi-arid areas [3]. The MODIS DB is offered to retrieve aerosol properties over brightly reflecting surfaces by using blue bands in which the surface reflectances are low enough to make such retrievals possible [4]. The main steps of the DB algorithm applied in the satellite processing stream are as follow: (1) apply the Rayleigh correction for terrain elevation to measured reflectances to account for variations in the surface pressure, and perform cloud screening by examining both the spatial homogeneity within a 3 × 3 pixel window and absorbing aerosol index values; (2) define the surface reflectance of a given pixel from a clear-scene database based upon its geolocation; (3) compare the surface reflectance at 412, 470, and 650 nm bands with the values recorded in a look-up table in dimensions consisting of satellite zenith, solar zenith, and surface reflectance, relative azimuth angles, single scattering albedo and aerosol optical

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thickness [4]. The best match is obtained with the iterative method and maximum likelihood method; (4) relate the AOD and Angstrom exponent (α) after the mixing ratio and aerosol models are determined. The particularity of the deep blue satellite retrieval algorithm was described in [3].

2.3 MODIS-AERONET Collocation

Two methods are used for arranging the MODIS and AERONET AOD data. Initially, AERONET measurements within +/- 30 minutes of the MODIS overpass time are averaged and compared against MODIS AOD retrievals averaged within a 55 km diameter centered over the AERONET sites. Using the mean method MAPSS also saves the mode of the quality flags from each pixel within the averaging region (55 km) to represent the quality flag for the collocated MODIS retrieval [13]. The quality flag mode is then used to filter the AOD data for only high quality retrievals. Secondly, the MODIS AOD retrieval near to the AERONET site is paired with the AERONET measurement that is near to the MODIS overpass time (central method). [13], find that there is little difference between the mean and central methods, so, to be consistent with prior research and maximize data volume the mean method is used for of this study.

After getting the collocated MODIS retrievals at all AERONET sites a quality filter is run. AERONET sites must have at least 15 high quality (flag 3 for Land, or flags 1, 2, or 3 for Ocean) MODIS retrieval pairs to be used in this study. To be considered a coastal site, AOD measurements from AERONET must be paired with both the MODIS Ocean algorithm at minimum once and the MODIS Land algorithm at minimum once over the whole time period of this research (2000-2010). For the approximately 11 year record of Terra-MODIS and AERONET AOD pairs from MAPSS, the result from the mean collocation method, that is consistent with [5], shows that 83, or approximately 26%, of the AERONET stations have MODIS retrievals from both the Land and Ocean algorithms, and therefore those sites are designated as coastal

4. Result and Discussion

Although previous MODIS analysis, over a global average, was valuable for understanding MODIS error characteristics ([15], [11], [12]), an examination of coastal regions shows a reduction in MODIS accuracy. Note that the MODIS Land algorithm allows negative values when retrieving AOD, even though negative AOD values are not physically possible. From 2000-2010 approximately 500 retrievals from MODIS when paired with AERONET over the coastal regions resulted in negative AODs and those retrievals are not included in the analyses.

After removing retrievals with quality flags below 3 for Land and below 1 for Ocean, MODIS AODs are highly correlated with the paired AOD from AERONET with $R^2$ of 0.8, regardless if AODs are retrieved over coastal region, from Ocean algorithm, Land algorithm, and Deep blue algorithm (Figure 2). Compared with AERONET AOD, MODIS AOD retrievals from the Ocean algorithm have a correlation coefficient ($R^2$) of 0.844 and a regression equation of $\tau_M = 0.91 \cdot \tau_A + 0.02$ (where subscripts A and M represent AERONET and MODIS respectively) for all the coastal sites, MODIS AODs from the Dark Target Land algorithm have an $R^2$ of 0.764 and linear regression $\tau_M = 0.95 \cdot \tau_A + 0.03$ for coastal stations, and $R^2$ of 0.652 and $\tau_M = 0.81 \cdot \tau_A + 0.04$ for the Deep blue algorithm. However, the Ocean AOD correlation is consistently greater than the Land AOD correlation for coastal stations. The reasons of the retrieval error in AOD are found to be the different surface characteristics. So, the underlying surface reflectance and aerosol models are the main factors which impact the accuracy of MODIS retrieval performance. Generally the MODIS Land algorithm with $R^2$ 0.744 and RMSE 0.1004 implements better than the Ocean algorithm with $R^2$ 0.844 and RMSE 0.0596 for coastal sites.

Summary statistics for MODIS and AERONET values for the entire data set as well as stratified by algorithm are presented. Results showed that AERONET had a slightly wider range (0.002 – 2.0650) as
compared to MODIS (0.7 - 3.192). MODIS values were 0.0136 ± 0.00069 greater than AERONET; approximately 25.49% of the total mean AOT (Table 1). The relative difference was larger in the dark target ocean algorithm (0.012, 27.79% relative error) and the dark target land algorithm (0.017, 27.3% relative error) as compared to the deep blue algorithm (0.020, 9.33% relative error).

Table 1. Descriptive Statistics for MODIS and AERONET AOT Variables by different algorithm

| Variables           | MODIS          | AERONET        | Difference | Relative Error, % |
|---------------------|----------------|----------------|------------|-------------------|
|                     | N   | Mean  | SD   | Minimum | Maximum | (Standard Error) |         |
| Dark Target Land Algorithm | 8214 | .207  | .181 | .000    | 1.797   | .017           | 27.30   |
| AERONET             | 8214 | .189  | .167 | .002    | 2.044   | (.0009)        |         |
| Dark Target Ocean Algorithm | 6200 | .154  | .144 | .001    | 3.192   | .012           | 27.79   |
| AERONET             | 6200 | .141  | .145 | .004    | 2.023   | (.0007)        |         |
| Deep Blue Algorithm | MODIS | 839  | .303 | .272    | .017    | .020           | 9.33    |
| AERONET             | 839  | .323  | .271 | .023    | 2.065   | (.0058)        |         |
| Combination result  | MODIS | 15253 | .191 | .177    | .000    | .013           | 25.49   |
| AERONET             | 15253| .177  | .171 | .002    | 2.065   | (.0006)        |         |

1N refers to sample size.
2SD refers to arithmetic standard deviation.
3Difference is calculated as MODIS - AERONET.
4Relative error of MODIS is calculated as (MODIS- AERONET)/AERONET

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Figure 2. Scatter plot of AERONET AOD (x-axis) and the quality flag filtered Terra-MODIS AOD (y-axis) from 2000-2010. In (A), (B) and (C) AODs in y-axis are respectively derived from MODIS dark target Land, dark target Ocean and deep blue products over the coastal AERONET station.

Reference

[1] Eck, T., Holben, B., Reid, J. and Dubovik, O. 1999. Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. J. Geophys. Res. 104, 31333_31349.

[2] Holben, B., Eck, T., Slutsker, I., Tanre, D., Buis, J. P. and co-authors. 1998. AERONET – a federated instrument network and data archive for aerosol characterization. Remote Sens. Environ. 66, 1_16.

[3] Hsu, N. C., Tsay, S. C., King, M. D., and Herman, J. R.: 2004. Aerosol Properties Over Bright-Reflecting Source Regions, IEEE T. Geosci. Remote, 42, 557–569, doi:10.1109/TGRS.2004.824067.

[4] Hsu, N. C., Tsay, S. C., King, M. D., and Herman, J. R.: 2006. Deep blue retrievals of Asian aerosol properties during ACE-Asia, IEEE T. Geosci. Remote., 44, 3180–3195.
[5] Ichoku, C., Chu, D., Mattoo, S., Kaufman, Y., Remer, L. and co-authors. 2002. A spatio-temporal approach for global validation and analysis of 1_4. DOI: 10.1029/2001GL013206.

[6] IPCC: Climate Change 2007: The physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp., 2007.

[7] Kaufman, Y. J., Tanre, D., Remer, L. A., Vermote, E. F., Chu, A., Holben, B. N.: 1997. Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging Spectroradiometer, Journal of Geophysical Research, 102, 17051-17067.

[8] Kahn, R., Garay, M., Nelson, D., Levy, R., Bull, M. and co-authors. 2011. Response to “Toward unified satellite climatology of aerosol properties. 3. MODIS versus MISR versus AERONET.” J. Quant. Spectrosc. Radiat. Transfer. 112, 901-909. DOI: 10.1016/j.jqsrt.2010.11.001.

[9] Kinne, S. 2003. Monthly averages of aerosol properties: a global comparison among models, satellite data, and AERONET ground data. J. Geophys. Res. 108, 4634, D20. DOI: 10.1029/2001JD001253.

[10] Koren, I. and Feingold, G. 2011. Aerosol-cloud-precipitation system as a predator-prey problem, P. Natl. Acad. Sci. USA, 108, 12227-12232, doi:10.1073/pnas.1101777108.

[11] Levy, R., Remer, L. and Dubovik, O. 2007. Global aerosol optical properties and application to Moderate Resolution Imaging Spectroradiometer aerosol retrieval over land. J. Geophys. Res. 112, 1_15. DOI: 10.1029/2006JD007815.

[12] Levy, R., Remer, L., Kleidman, R., Mattoo, S., Ichoku, C. and co-authors. 2010. Global evaluation of the Collection 5 MODIS dark-target aerosol products over land. Atmos. Chem. Phys. 10, 10399_10420. DOI: 10.5194/acp-10-10399-2010.

[13] Petrenko, M., Ichoku, C., and Leptoukh, G. 2012. Multi-sensor Aerosol Products Sampling System (MAPSS), Atmospheric Measurement Techniques, 5, 913-926, doi:10.5194/amt-5-913-2012.

[14] Pope, III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., and Thurston, G. D. 2002. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution, JAMA, 287, 1132–1141, doi:10-1001/pubs.JAMA-ISSN-0098-7484-287-9- joc11435.

[15] Remer, L. A., Kaufman, Y. J., Tanre, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R. R., Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermote, E., and Holben, B. N. 2005. The MODIS aerosol algorithm, products, and validation, J. Atmos. Sci., 62, 947–973, doi:10.1175/JAS3385.1.

[16] Remer, L. A., Kleidman, R. G., Levy, R. C., Kaufman, Y. J., Tanr´ e, D., Mattoo, S., Martins, J. V., Ichoku, C., Koren, L., Yu, H., and Holben, B. N. 2008. Global aerosol climatology from the MODIS satellite sensors, J. Geophys. Res.-Atmos., 113, D14S07, doi: 10.1029/2007JD009661.

[17] Salomonsen, V., Barnes,W., Maymon, P., Montgomery, H., and Ostrow, H. 1989, MODIS – Advanced facility instrument for studies of the earth as a system, IEEE T. Geosci. Remote., 27, 145–153, 1989.

[18] Smirnov, A., Holben, B. N., Eck, T. F., Dubovik, O. and Slutsker, I. 2000. Cloud-screening and quality control algorithms for the AERONET database. Remote Sens. Environ. 73, 337_349. DOI: 10.1016/S0034-4257(00)00109-7.
[19] Tanré, D., Kaufman, Y.J., Herman, M., Mattoo, S., 1997. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiance. Journal of Geophysical Research 102, 16971e16988.

[20] Tibbetts, J. 2002. Coastal cities: living on the edge. Environ. Health Perspect. 110, 674_681.