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COMPARISON OF AEROSOL PRODUCTS RETRIEVED FROM AERONET AND MODIS OVER AN URBAN AREA IN HANOI CITY, VIETNAM

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Abstract

To understand the dynamics of aerosols and their associated influence on regional and global climatic conditions requires the knowledge of spatial and temporal distributions of aerosols on regional and global scales. In this study, the satellite-based MODIS AODs retrievals level 2 products from Terra (MOD04-10 km) and Aqua (MYD04-10 km) satellites were inter-compared with the ground-based AERONET AODs (level 2) over Nghia Do station located in an urban area of Hanoi city, Vietnam for the period of 2010–2016. The Terra AODs showed good-match with the ground-based AODs measurements (slope = 0.830, intercept = 0.099, RMSE = 0.260, R^2 = 0.673, and RMB = 0.970). However, the Aqua AODs expressed systematically the underestimation of AERONET AODs (slope = 0.556, intercept = 0.184, RMSE = 0.390, R^2 = 0.408, and RMB = 0.810). All MODIS AODs indicated the moderate correlation with AERONET AODs (slope = 0.683, intercept = 0.147, RMSE = 0.330, R^2 = 0.520, and RMB = 0.890). Although MODIS AODs followed well the monthly variations of AERONET AODs, the relatively high discrepancy between MODIS and AERONET AODs could be observed during the winter months.

Keywords: aerosol products; MODIS AODs; AERONET AODs; inter-comparison.

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1. Introduction

The knowledge of spatial-temporal distributions of aerosols is vitally important for both air quality and climate applications. Due to sparse sampling by ground-based measurements, satellite remote sensing techniques play an important role to provide systematic retrieval of aerosol optical properties on regional and global scales. Satellite observations could provide information over the larger spatial domain while the ground-based measurements just could provide information over a particular limited region. However, in order to confirm the usefulness of satellite-based aerosol optical depth (*AOD*) for air quality and climate application, it is important to characterize the performance of satellite-based *AOD* product for daily basis as well as seasonal and annual *AOD* cycles by comparing the satellite product to ground-truth observations.

The MODerate Resolution Imaging Spectroradiameters (MODIS) aboard Terra and Aqua satellites observe the earth-atmosphere system twice daily, provide *AOD* estimations for both land and ocean. Comparison and evaluation of MODIS AOD products with the ground-based *AOD* measurements obtained from collocated ground-based sunphotometers NASA's Aerosol Robotic NETwork

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(AERONET) have been studied globally and locally [1–11]. However, according to our intensive literature review, there have been few studies conducted in Vietnam relating to MODIS AOD satellite data so far. To our knowledge, there are only two researches that compare MODIS AOD and ground-based AERONET AOD measurements [12]. However, these researches used MODIS AOD Collection 5 product. Recently, the latest MODIS AOD Collection 6.1 has been released with modified algorithm for aerosol retrieval over land surface. Therefore, in present study, the fine spatial resolution (10 km × 10 km) MODIS AOD products in the latest collection 6.1 MOD04 and MYD04 are inter-compared with AERONET AOD to characterize the deviations between satellite-retrievals and ground-based measurements for the first time over the urban area in Hanoi city by two means: (1) the correlation and level of agreement between collocated AERONET AOD measured during MODIS overpass hours with the MODIS AOD; and (2) the ability of monthly-averaged MODIS AOD to track AERONET AOD.

2. Data and methods

2.1. MODIS dark target 10 km level 2 products

MODIS data includes different processing levels: (1) level 1.0 is geolocated and calibrated brightness temperature and radiances); (2) level 2.0 is derived geophysical data products; and (3) level 3.0 is gridded time-averaged products. This study employed the latest MODIS AOD level 2 product collection 6.1 MOD04 and MYD04 instantaneous AODs at the wavelength of 550 nm using Dark target (DT) algorithm.

The "Level 2" MODIS *high-resolution aerosol product* is geophysical derived at 10 km spatial resolution (at nadir), and known as MOD04_10 km (for Terra) and MYD04_10 km (for Aqua). Collectively, referred to as MxD04, the data used here (from Jan 2010 to December 2016 which corresponding to the period that the AERONET AOD data is available for our study area) are products from consistent application of the DT retrieval algorithm [13, 14], instrument calibration, and computer processing environment. Although the data are from Collection 6.1, the MODIS DT retrievals of aerosols use two separate algorithms for land and ocean. The goal of the DT land algorithm is to use the lookup table to determine the conditions that best mimic the MODIS-observed spectral reflectance by interpreting the contrast of aerosol (relatively high) against the dark surface back ground. For the 10 km (nominal at nadir) retrieval, MODIS measured reflectance are organized into nominal 10 km - 10 km retrieval boxes which include 20 × 20 0.5 km pixels. 400 pixels in the box are pixel-by-pixel masked to remove the undesirable pixels including clouds, snow/ice, and other bright surfaces. These 400 pixels are separated to land and water pixels. 20% of the darkest remaining pixels and 50% of the brightest remaining pixels are discarded using 0.66 micrometer channel for brightness check. The DT 10 km retrievals algorithm required at least 51 pixels over land for performing best quality aerosol retrieval.

A "dark-target" retrieval algorithm over land retrieving aerosol properties uses three spectral channels centered at 0.47, 0.66, and 2.13 micrometer wavelength which are mainly influenced by surface reflectance and aerosol type. With the assumption that the 2.13 micrometer wavelength contains the information about surface reflectance as well as coarse-mode aerosol, the DT algorithm attempts to retrieve when the observed reflectance at 2113 nm is between 0.01 and 0.25. For the surface properties, the algorithm makes a major assumption (primarily for vegetated surfaces) that the surface reflectance in the visible wavelength (0.47 and 0.65 micrometer) are the function of a shortwave-infrared (SWIR) MODIS channel (2113 nm), Normalized Differential Vegetation Index (NDVI, Karnieli et al., 2001) calculated using MODIS SWIR channels centered at 1243 nm and 2113 nm [13] and scattering angle. Collection 6.1 have added an urban surface parametrization as a branch of retrieval algorithm. The urban retrieval is performed whenever 20% of the pixels in a retrieval box are identified as urban.

Aerosol model type and a model spectral surface reflectance appropriate for the regional vegetation indices and season are prescribed to present Look Up Table (LUT). The DT algorithm compares the observed MODIS spectral reflectance with spectral reflectance from LUT to find the best match. From the lookup table, the atmospheric path reflectance (ρa), atmospheric transmission (T), normalized downward flux (F), and atmospheric backscattering ratio (s) (for the fine model and coarse model separately) are interpolated for angle, resulting in six values for each parameter, corresponding to aerosol loading (indexed by τ at 0.55 μm). For discrete values of η between -0.1 and 1.1 (intervals of 0.1), the algorithm attempts to find the τ at 0.55 μm and the surface reflectance at 2.12 μm that exactly matches the MODIS measured reflectance at 0.47 μm. There will be some error, ε, at 0.65 μm. The solution is the one where the error at 0.65 μm is minimized. The primary products are τ (τ0.55), η (η0.55), and the surface reflectance (ρs2.12). The error ε is also noted.

2.2. AERONET AODs product

The AERONET (Aerosol Robotic NETwork) is ground-based remote sensing aerosol networks which employs CIMEL sun-sky spectral radiometer to measure the direct solar radiance at nine wavelength and the sky radiance at four wavelengths using standard AERONET protocols [1]. *AOD* at each of the nine wavelengths (except 940 nm) are calculated using the direct solar radiance measurements based on Beer-Lambert-Bouguer law. The AERONET AOD retrieval corrects optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous pollutants. Most sun-photometers make a measurement every 15 minutes during the day at several wavelengths, from which *AOD* values are derived with a precision of the order of 0.01 to 0.02 [1]. AERONET data is available at three levels: Level 1.0 (unscreened), Level 1.5 (cloud screened), and Level 2.0 (cloud screened and quality assured). In this study, we used the Level 2.0 AERONET data. In our study, we used the data for the period of 2010–2016 obtained from Nghia Do station - an AERONET measurement site in Ha Noi (21.04° N, 105.79° E) which operated since 2010. The data was downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/).

2.3. Method for comparison between MODIS satellite-based and AERONET ground-based AODs

The ground-based AERONET AOD and satellite-based MODIS AOD data are obtained from different sources which have different temporal and spatial resolutions. For performing the correlation analysis between these two datasets, it is necessary to pre-process these datasets to be consistent in space and time. Hence, collocating the air mass seen by MODIS sensor from the space over the study area with the one measured by AERONET from the ground simultaneously is required. First, only AERONET AOD ground-based measurements and MODIS AOD satellite measurements taken on the same day was considered for pairing. For each day, the distance was calculated between the latitude and longitude of each of the satellite measurements made on that day and each of the ground-based data. Next, for ground-based station on each day, the closest satellite measurement for that day was found. This separation requirement is consistent with a lagged correlation analysis conducted on the surface measurements by Anderson et al. [15]. Once AERONET station was paired with satellite measurements spatially, time was taken into account. In this study, we averaged the MODIS AOD values at the 10 km × 10 km spatial resolution over the 50 km × 50 km grid box centered at AERONET station [3].

Because the *AOD* values can vary substantially during the course of a single day, the MODIS AOD data can be compared with the reference AERONET data collected only at comparable times of the day. The time matching of the AERONET AOD data with the MODIS AOD retrievals was made following the method of Ichoku et al. [16]. In particular, the AERONET data was averaged within ±30 min of the satellite's passing. After this averaging, AERONET AOD measurements at 0.50 μm were interpolated to a common wavelength of 0.55 μm using the values of the Ångström exponents also available in the AERONET data set as the following equation:

$$AOD_a = AOD_b\left(\frac{a}{b}\right)^{-\alpha} \tag{1}$$

where $a = 0.55\,\mu$m for MODIS, $b = 0.50\,\mu$m for AERONET, and α is the (0.44-0.87 μm) Ångström exponent [17].

Thus, over 7 year period (from 2010 to 2016), we obtained 105,107 collocated data set for MODIS (Terra)-AERONET and MODIS (Aqua)-AERONET, respectively.

This interpolation is necessary for allowing direct comparison of the AERONET data with the MODIS retrievals at the same wavelength. For satellite data, MODIS AOD was averaged over a square has the side of 40 km with a sunphotometer in its center. The mean values of the collocated spatial and temporal ensemble were then used in validation. Here linear regression analysis was performed for MODIS AOD with respect to AERONET AOD using the following equation:

$$AOD_{\text{MODIS}} = m \times AOD_{\text{AERONET}} + c \tag{2}$$

where $\text{AOD}_{\text{MODIS}}$ and $\text{AOD}_{\text{AERONET}}$ represent the AODs from MODIS and AERONET, respectively; m is the slope; and c is the vertical intercept. The regression coefficient (R^2), which is the square of the correlation coefficient, indicates the correlation between MODIS and AERONET AODs. All of these quantities (m, c, and R^2) serve as useful indicators of the local spatial characteristics of the aerosol parameter (*AOD*) at a particular location and time [3]. The slope (m) of the linear regression equation reveals how close the assumed aerosol model over a particular region is to the local aerosol type, and the intercept (c) indicates the error caused by surface reflectance [5–11]. The linear regression equation therefore provides information concerning the factors that affect the correlation. If there is a perfect correlation between $\text{AOD}_{\text{MODIS}}$ and $\text{AOD}_{\text{AERONET}}$ then the value of c would be 0, the values of R^2 and m would be 1 [5]. Large intercepts are due to large errors in surface reflectance and at ground surface reflection the retrieval algorithm is biased towards low *AOD* values, which are indicated by non-zero intercepts that may be associated with an inappropriate assumption or with calibration error [3, 5]. In contrast to real situations, where the slope in the retrieval algorithm is other than unity this may indicate some irregularities between the optical properties and the aerosol microphysical properties used in the retrieval algorithm.

In addition to using linear regression, we also computed the root mean square error (RMSE) between the MODIS and AERONET AOD observations. The RMSE is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(AOD_{(\text{MODIS})i} - AOD_{(\text{AERONET})i}\right)^2} \tag{3}$$

where n is the number of observations.

Overestimation or underestimation of retrievals can be quantified by calculating the root mean bias (RMB), which is defined as:

$$\text{RMB} = \frac{\overline{AOD}_{\text{MODIS}}}{\overline{AOD}_{\text{AERONET}}} \tag{4}$$

If RMB < 1, then this represents an underestimation, and if RMB > 1, this represents an overestimation.

3. Results

Fig. 1 expresses the relationship between the Terra AOD and Aqua AOD retrievals against AERONET derived AODs from 2010 to 2016. In Fig. 1, the black and red colored lines represent 1-1 line, the linear regression of the scatter plot. It is seen that the coefficient of determination R^2 values are 0.673 and 0.408 for Terra AOD and Aqua AOD, respectively. The MODIS/AERONET regression slopes and intercepts for Terra are significantly better than those for Aqua. The slopes of regression lines are 0.830 and 0.556 for Terra and Aqua, respectively; and the intercepts for Terra and Aqua are 0.184 and 0.099, respectively.

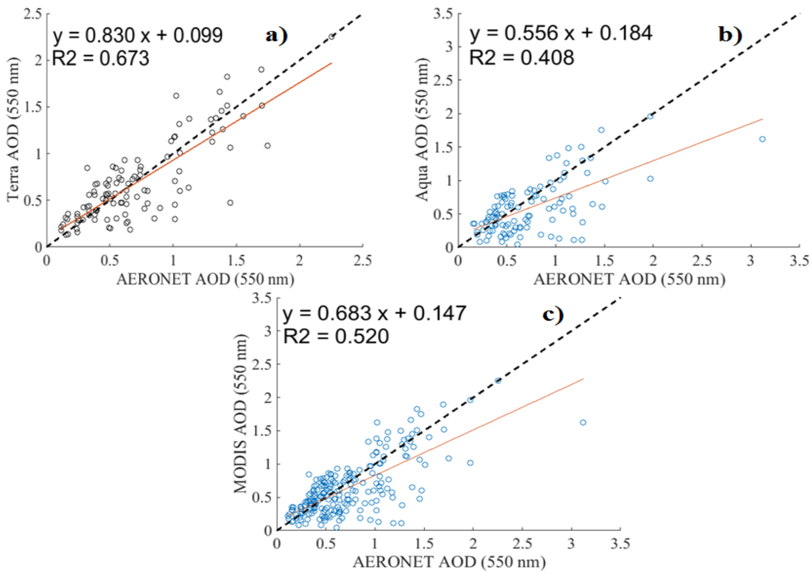

Figure 1. Correlation plots of MODIS (Terra and Aqua) AOD retrievals against AERONET AODs from 2010 to 2016. (*The red solid lines indicate linear regression and the dotted black lines represent 1:1 lines*)

In addition, it can be seen from Table 1 that the RMSE values between the ground-based AERONET and MODIS AODs are 0.260 and 0.390 for Terra and Aqua, respectively. The RMB value of Aqua retrieval AODs (0.810) indicates the systematical underestimation of the ground-based AERONET AOD measurements. However, Terra AODs shows good match with the AERONET AODs with RMB value of 0.970 which is close to unity. In addition, the correlation plots of all MODIS AODs retrievals against the measured AODs are shown in Fig. 1c. As the effect of combination of both Terra and Aqua AODs, the R^2, slope, intercepts, RMSE and RMB values of all MODIS AODs are better than those for the case with only Aqua AODs considered (0.520, 0.683, 0.147, 0.330, and 0.890, respectively). Levy et al. [8] found no significant difference between AERONET/Terra agreement and AERONET/Aqua agreement in their global Collection 5 (C5) validation study. However, they reported that Terra measured higher (lower) AOD than AERONET over land up until (after) 2004. The Terra AOD drift was attributed to radiance calibration drift, especially in the blue channel. This drift has been reduced for MODIS C6 and C6.1, but the low bias for Terra AOD over land is expected to persist [18].

Table 1. Result of regression analysis for MODIS (Terra and Aqua) derived *AOD* against AERONET measurements at 550 nm from 2010–2016

Year	*n*	Slope	Intercept	R^2	RMSE	RMB
Terra	105	0.830	0.099	0.673	0.260	0.970
Aqua	107	0.556	0.184	0.408	0.390	0.810
Terra & Aqua	212	0.683	0.147	0.520	0.330	0.890

At Nghia Do station, there are totally 212 collocated MODIS-AERONET data pairs. It can be seen from Table 2 that the number of collocated MODIS-AERONET data depends on seasons and local weather condition in Hanoi. During the early winter months (October, November, and December), local weather are featured with clear-sky and low relative humidity. This dry weather condition is great advantage for satellite to observe the Earth as well as measure the solar radiation from the ground. Therefore, the number of collocated MODIS-AERONET data pairs in those months are relatively larger than those in the other months in winter. In addition, during the late winter months (January, February, and March), the drizzly weather is featured with cloudy and foggy sky. Therefore, the MODIS-AERONET data pairs are relatively smaller than those in the early winter months. During the monsoon months which characterized by hot and humid weather with abundant rainfall, the thick cloud from summer abundant rainfall is the cause of significantly low AODs data pairs in June, July, August, and September (10, 7, 15, and 3 data pairs, respectively).

Table 2. Statistical summary of monthly averaged AODs for MODIS and AERONET at Nghia Do station from 2010 to 2016

Month	Number of data pairs	Mean of MODIS AODs	STD(*) of MODIS AODs	Mean of AERONET AOD	STD of AERONET AODs	Mean of MODIS-AERONET AOD	STD of MODIS-AERONET AODs
JAN	14	0.600	0.295	0.830	0.332	−0.230	0.342
FEB	20	0.525	0.226	0.677	0.264	−0.152	0.344
MAR	7	0.867	0.462	1.214	0.426	−0.347	0.340
APR	20	0.881	0.535	0.940	0.694	−0.059	0.340
MAY	34	0.550	0.324	0.525	0.300	0.025	0.329
JUN	10	0.973	0.772	0.975	0.881	−0.002	0.340
JUL	7	0.509	0.520	0.370	0.308	0.138	0.295
AUG	15	0.621	0.278	0.673	0.319	−0.052	0.290
SEP	3	0.708	0.238	0.636	0.277	0.072	0.282
OCT	28	0.854	0.394	0.883	0.342	−0.029	0.279
NOV	26	0.514	0.391	0.618	0.338	−0.105	0.253
DEC	28	0.438	0.287	0.621	0.334	−0.183	0.259

(*): STD = Standard deviation

The monthly-averaged *AOD* using all MODIS and AERONET measurements (independent of collocation) are calculated to assess MODIS ability to track monthly-averaged AERONET AOD over the 7 years study period (Fig. 2). In Fig. 2, the monthly-averaged MODIS AODs, AERONET

AODs, and the discrepancy between satellite-based and ground-based AODs are illustrated using dash blue line, red solid line, and dash green line, respectively. AODs measurements form MODIS and AERONET range from 0.438 to 0.973 and from 0.370 to 1.214, respectively with standard deviation values range from 0.226 to 0.772 and 0.264 to 0.881, respectively. Fig. 2 shows the peaks of MODIS and AERONET AOD retrieval values occuring at the beginning of winter (October) and at the end of winter (March) with moderate standard deviation values (from 0.338 to 0.462). In addition, the measured AODs of both MODIS and AERONET in June are another high peak (0.973 and 0.975) with large standard deviation values (0.772 and 0.881). Pham et al. [12] also reported similar findings that *AOD* load at Nghia Do station were high during the beginning of winter months (October and November), and during the late winter months (March and April). Tran et al. [19] also found that *AOD* load in Hanoi were high in October and March because of monsoon circulation affection and biomass burning. Dust lifting and suspending in the air is result of North-East monsoon flows in October causing the stable temperature and dry weather in Hanoi. In addition, Huang et al. [20] and Le et al. [21] reported the peak of biomass burning in Southeast Asia and in Vietnam in March.

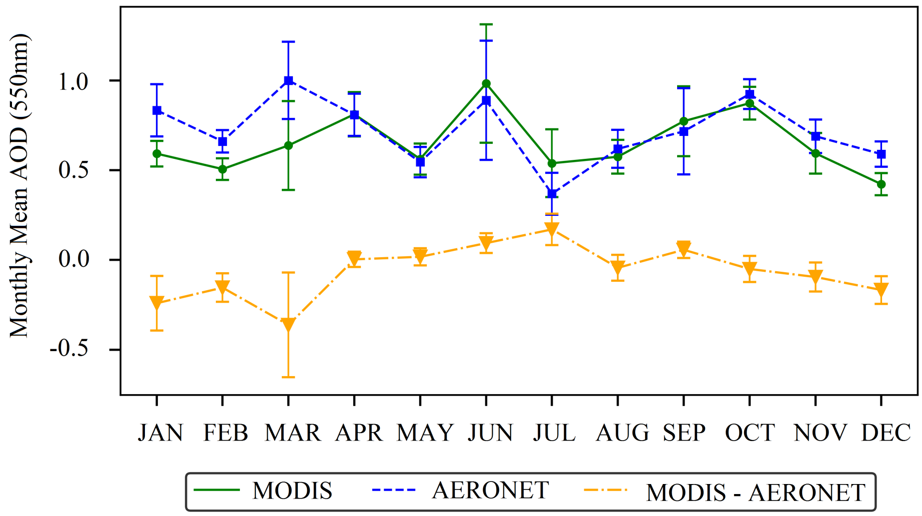

Figure 2. Monthly AODs for MODIS and AERONET at Nghia Do station from 2010 to 2016 with error bars indicating standard deviation values

It can be seen from Fig. 2 that MODIS AODs are able to capture the seasonal variations with the AERONET AODs. Additionally, MODIS AODs shows good-match with the measurements AERONET AODs for May and Jun with the small difference between MODIS and AERONET AOD (0.025 and −0.002, respectively). In general, MODIS AODs retrievals underestimate the ground-based AOD measurements for the remaining months of the year except for July and September. The discrepancy values of MODIS and AERONET AODs ranges from −0.002 to −0.347 with the standard deviation values range from 0.253 to 0.344. The difference between satellite-based and ground-based AODs observations is generally high during winter with MODIS-AERONET AODs values of −0.347, −0.230, −0.183, −0.105, and −0.152 in March, January, December, November, and February, respectively. More et al. [22] compared the aerosol products retrieved from AERONET and MODIS over a tropical urban area in India and found similar findings that "average monthly variation of MODIS and AERONET AODs show similar pattern of variation with MODIS AOD values systematically less than those of AERONET AODs during winter". The relative weak reflected signals from the atmosphere (which is easily distracted by the high surface reflectance) are ultilized to obtain aerosol properties. In addition, contributions of clouds and high concentrations of particulate matters would be a factor leading to the improper assumption of surface reflectance and selection of aerosol type over polluted area because the high loading of particulate matters prevents the transferring of radiation from land to the satellite. Therefore, the high concentrations of particulate matters in the atmosphere in dry and cool weather with little rainfall in winter [23] would the possibly contribute to these discrepancies.

4. Conclusions

This paper made the inter-comparison between the MODIS AODs retrievals level 2 products from Terra (MOD04-10 km) and Aqua (MYD04-10 km) onboard satellites and the ground-based AERONET AODs obtained from Nghia Do station, Hanoi, Vietnam. The inter-compared results suggest that Terra AODs shows good-match with the ground-based AODs measurements (slope = 0.830, intercept = 0.099, RMSE = 0.260, R^2 = 0.673, and RMB = 0.970). However, Aqua AODs retrieval expressed systematically the underestimation of AERONET AODs (slope = 0.556, intercept = 0.184, RMSE = 0.390, R^2 = 0.408, and RMB = 0.810). As the effect of Terra-Aqua AODs combination, all MODIS AODs indicate the moderate correlation with AERONET AODs (slope = 0.683, intercept = 0.147, RMSE = 0.330, R^2 = 0.520, and RMB = 0.890). Although MODIS AODs were able to capture the monthly variations of AODs load, the relatively high discrepancy between MODIS and AERONET AODs was observed during the winter months. It is suggested that in future research, AODs measurements from Terra and Aqua MODIS retrievals would be useful to characterize AODs spatial and temporal distributions with further investigation about the systematic errors in MODIS product during winter time.

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