INTER-COMPARISON BETWEEN MODIS SATELLITE-BASED AND AERONET GROUND-BASED AEROSOL OPTICAL DEPTH PRODUCTS IN VIET NAM

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Abstract. Although a number of studies have extensively inter-compared the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-based aerosol optical depth (AOD) with the Aerosol Robotic Network (AERONET) ground-based AOD on both global and regional scales, almost no similar studies have been conducted for Vietnam - a humid subtropical climate region. For the first time, inter-comparison between the MODIS Terra and Aqua Collection 6.1 (C6.1) Dark Target (DT) 10 km, Deep Blue (DB) 10 km, and merged DT-DB 10 km with the AERONET AODs has been performed in different areas with different surface types and different climatic characteristics in Vietnam. Three investigated AERONET stations are Nghia Do (urban), Son La (mountainous rural), and Bac Lieu (coastal urban) with the studying periods of 2010-2016, 2012-2017, and 2010-2017, respectively. Our findings showed the better performances of DB algorithm than those of DT and DT-DB products in the urban area. Additionally, all MODIS AOD algorithm performed worse over the coastal area compared to those in the non-coastal areas. Generally, the ability of all the MODIS AODs to catch up the monthly-mean AERONET AODs has been expressed in this study.

Keywords: Aerosol optical depth (AOD), MODIS Collection 6.1, MODIS AOD retrieval algorithms, AERONET AOD.

Classification numbers: 3.4.5, 3.8.2.

1. INTRODUCTION

The limited number of air quality monitoring ground-based stations has constrained the assessment of the spatial and temporal variation of air quality in Vietnam, which leads to the difficulty in air quality management. Fortunately, satellite observations have shown the potential to estimate air pollutant concentrations near the surface with high spatio-temporal resolution and global coverage. Many studies in the world have observed that the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) has strong positive relationships with
particulate matter (PM) concentrations observed on the surface [1 - 5]. Therefore, it is vitally crucial to carry out the researches on the accuracy of MODIS AOD products as the basis for the potential application of MODIS AOD products to estimate the surface PM pollution in Viet Nam.

Among the powerful satellite products used to monitor the global aerosol loadings, MODIS AOD products are the most popular ones because of their high accuracy for both fine and coarse aerosol mode [6]. On the other hand, the Aerosol Robotic NETwork (AERONET) could provide a unique benchmark for validation of satellite aerosol retrievals. Therefore, the comparisons for AODs derived from MODIS and AERONET have been made by a number of studies for many locations over the world [7 - 11], and their results have shown that the agreements between MODIS and AERONET AODs could vary from fairly good to bad depending on the aerosol type with the accuracy of retrieval results were different with $\Delta \tau_{\text{land}} = \pm 0.05 \pm 0.20\tau$ over land [2] and $\Delta \tau_{\text{ocean}} = \pm 0.03 \pm 0.05\tau$ over ocean [7].

There have been very few studies on the validation of satellite-based AOD using AERONET AODs in Viet Nam. Up to date, there has been only one study [9] that evaluated Visible Infrared Imaging Radiometer Suite (VIIRS) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) aerosol products at three AERONET stations in Viet Nam. However, that study has not investigated the widely-used MODIS AOD products. In another study [10], the MODIS AODs in the older collection were compared with the AERONET AODs version 2 products. However, the information on the MODIS AOD retrieval algorithm and the accuracy of MODIS AODs regarding the algorithm was very limited. Our study will address these knowledge gaps by evaluating the performances of (10km x 10km) MODIS AOD products in the latest collection C6.1 for the three AERONET stations in Viet Nam with various surface types and climate characteristics including Nghia Do, Son La (both located in the North of Viet Nam), and Bac Lieu (located in the South of Viet Nam) which are corresponding to the urban, mountainous rural, and coastal urban areas, respectively. This first ever study in Viet Nam will comprehensively evaluate the performance of MODIS AOD C6.1 Dark Target (DT) 10 km, Deep Blue (DB) 10 km, and merged DT-DB 10 km by performing the inter-comparison with the AERONET AODs to characterize the deviations between satellite-based and ground-based measurements. Therefore, the objectives of this study were to investigate: (1) the correlation and level of agreement between the collocated AERONET AODs measured during MODIS overpass hours with the MODIS AODs; and (2) the ability of the MODIS AODs to track the seasonal variation trends of AERONET AODs.

2. MATERIALS AND METHODS

2.1. Study area

Three AERONET stations (Nghia Do at 105.80 E/21.05 N, Son La at 103.91 E/21.33 N, and Bac Lieu at 105.73 E/9.28 N) located in different climatic zones in Viet Nam with different surface types are considered for analysis in relation to MODIS aerosol products. The investigated time period of Nghia Do, Son La, and Bac Lieu were 2010 - 2016, 2012 - 2017, and 2010 - 2017, respectively. Nghia Do AERONET station is situated in a populous urban area in Ha Noi which is the capital of Viet Nam and the second largest city of the country. Son La AERONET station is located in the mountainous rural area of Son La province with dense vegetable coverage. Both Ha Noi and Son La are in the North of Viet Nam with a rainy season from May to September, dry season from November to March, and transition in April and October. On the other hand, Bac Lieu is a coastal urban station located in the South of Viet Nam.
The climate of the South features two seasons during a year: rainy season (from May to October) and dry season (the remaining months). These stations are chosen as the studying areas because they represent different climatic zones and different surface types. Additionally, they have the long AERONET data records.

2.2. Data processing and validation

Because AERONET AODs data are ground-based measurements, thus AERONET AODs have been widely used as the benchmark to verify MODIS AODs. This study employed the latest MODIS AOD level 2 C6.1 product at the wavelength of 550 nm using the Dark Target (DT), Deep Blue (DB), and DT-DB combined algorithms. In this study, the MODIS operational aerosol products at 10 km spatial resolution including DT 10 km, DB 10 km, and DT-DB 10 km were downloaded from the Atmospheric Archive & Distribution System (LAADS) (https://ladsweb.modaps.eosdis.nasa.gov/). With the aim of providing qualified and adequate data, this study used the Level 2.0 AERONET AODs data at 500 nm which was downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/). AERONET AOD is ground-based measurements with retrieval corrects optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous pollutants. After AERONET AODs and MODIS AODs were collected, this study applied the method described in [12] to spatially and temporally collocate AERONET AODs and MODIS AODs.

Linear fitting for MODIS AOD with respect to AERONET AOD is one of the main methods used in this study for validating the precision and accuracy of MODIS AODs [7-11]. All of the quantitative parameters (slope, intercept, and R^2) serve as useful indicators of the local spatial characteristics of the aerosol parameter (AOD) at a particular location and time [7]. The regression coefficient (R^2), which is the square of the correlation coefficient, indicates the correlation between MODIS and AERONET AODs. Beside the linear regression analysis, ratio falling within the expected error (EE) envelope was also used to evaluate the difference of MODIS AODs products against AERONET AODs. Additionally, several indices including root mean square error (RMSE) and root mean bias (RMB) were selected to verify the accuracy and precision of MODIS AODs products.

3. RESULTS AND DISCUSSION

3.1. Overall agreement between MODIS and AERONET AODs

Figure 1 showed the statistical summary for the comparison between MODIS AOD products and AERONET AOD observations. In Fig. 1, the orange dashed, red solid, and blue dash lines are the 1:1 line, linear regression of the scattering dots, and EE range, respectively. However, neither of the products consistently outperform the others at the studying areas. DT and DT-DB products expressed almost identical values of the investigated statistics, and similar patterns of scatter plots, which was also reported by Zhang et al. [11]. At all investigated stations, although there were small differences in terms of R^2, RMSE, DT and DT-DB algorithms had significantly higher number of collocations than that of DB algorithm. It is noticed that the number of collocations of DB AOD product at the Bac Lieu - an urban coastal station, was significantly low. This result can be explained that the heterogeneity of the underlying surface over the coastal urban areas causes the difficulties in accurately determining the surface reflectance [11]. Additionally, all three MODIS AOD products substantially overestimated aerosol loading at Bac Lieu station (the RMB values were from 1.246 to 1.302).
Zhang et al. [11] also reported the high RMB values of C6 DB 10 km in Zhongsan University (about 1.37). On the other hand, the MODIS AOD underestimated the aerosol loading at Son La station (RMB values were about 0.87).

At Bac Lieu and Son La stations, DT and DT-DB products had higher collocated data falling within the EE envelope than the DB product, which indicated the superior performances of DT and DT-DB than the DB product. The percentage of collocated data falling within the EE envelope ranged from 41.436 to 51.724% at Bac Lieu station, and from 48.673% to 59.292% at Son La station.

These results were similar with the previous study [13]. The number of collocations within EE over the South East Asia for DT, DB, the merged DT-DB 10 km of C6 were 51 %, 61 %, and 52 %, respectively [13]. The RMSE values at Bac Lieu station (from 0.137 to 0.152) were close to the RMSE values of DT and DT-DB MODIS AOD of C6 over the South East Asia [13], and
smaller than the RMSE values at Son La station (from 0.241 to 0.282) and Nghia Do station (from 0.175 to 0.195). Tao et al. [14] also reported the RMSE at various AERONET sites in China expressing a wide range from 0.156 to 0.315. However, concerning the other remaining statistics, the significant lower $R^2$ values, substantial larger RMB, and lower collocation data within EE at Bac Lieu station compared with the corresponding statistics at Nghia Do and Son La stations indicated that the performances of MODIS products over the coastal site were inferior compared to those at the non-coastal sites, which is consistent with the results reported by the other studies [11, 15]. The $R^2$ values at Nghia Do and Son La stations (from 0.805 to 0.875) were close to the results of C6 DT and DT-DB 10 km (about 0.88) in China [11]. The $R^2$ values at these two stations were substantially higher than those at Bac Lieu station (from 0.657 to 0.684). Noticeably, at Nghia Do station, although DB slightly underestimated the aerosol loading, DB product showed significant higher collocated data within EE (72 %) than DT and DT-DB product (around 59 %). The higher data within EE envelope, higher $R^2$ value and smaller RMSE value of DB product than the remaining two AOD products at Nghia Do station would indicate better performances of DB in urban area.

3.2. Inter-comparison between seasonal mean of MODIS and AERONET AODs

The ability of monthly mean MODIS AODs to capture monthly mean AERONET AODs was shown in Fig. 2. All three MODIS AODs products expressed the ability to track the monthly variations of AERONET AODs at three sites. Similar to overall agreements of MODIS DT and MODIS DT_DB AODs compared with AERONET AODs, these two product also displayed almost identical monthly variation patterns.

![Figure 2](image)

Figure 2. Monthly mean MODIS AOD, AERONET AOD at 550 nm, along with monthly mean of their difference for: DT, DB, and DT-DB algorithms in three study locations. (Note: solid green line: MODIS data; dash blue line: AERONET data; and dash and dot yellow line: discrepancy between MODIS and AERONET AODs).

Generally, aerosol loading at Nghia Do and Son La stations were higher than that of Bac Lieu station. At Nghia Do station, the ranges for AOD measurements of MODIS DT, DB, and
AERONET were from 0.486 to 1.094, from 0.401 to 0.863, and from 0.409 to 1.054, respectively, with the ranges of standard deviation values being from 0.227 to 0.764, from 0.122 to 0.696, and from 0.212 to 0.864, respectively. Meanwhile, at Son La station, the ranges for MODIS DT, DB, and AERONET AODs were from 0.140 to 1.029, from 0.159 to 1.017, and from 0.147 to 1.169, respectively, with the ranges of standard deviation values being from 0.031 to 0.531, from 0.009 to 0.720, and from 0.020 to 0.604, respectively. The aerosol loading at Bac Lieu station was relatively lower than those at the two other northern stations with the ranges for MODIS DT, DB, and AERONET AODs were from 0.155 to 0.462, from 0.155 to 0.460, and from 0.121 to 0.376, respectively with the ranges of standard deviation values were from 0.046 to 0.214, from 0.039 to 0.315, and from 0.021 to 0.159, respectively. In addition, the seasonal mean MODIS AODs at Nghia Do and Son La was consistently larger than those values at Bac Lieu station as shown in Table 1. The seasonal mean of MODIS DT and MODIS DT-DB AODs in both dry and rainy season were lower than 0.4 at Bac Lieu, while the smallest seasonal mean values at Nghia Do and Son La was 0.573. Similarly, the mean seasonal values of DB AODs at two Northern AERONET stations were larger than the largest values at Bac Lieu (0.427).

Table 1. Statistical summary (mean ± standard deviation) of seasonal mean AODs for MODIS and AERONET.

| Product | SEASON | NGHIA DO | SON LA | BAC LIEU |
|---------|--------|----------|--------|----------|
|         | MODIS  | AER(*)   | MODIS-AER | MODIS  | AER    | MODIS-AER | MODIS  | AER    | MODIS-AER |
| DT      | Dry    | 0.695 ± 0.335 | 0.671 ± 0.353 | 0.024 ± 0.181 | 0.807 ± 0.450 | 0.964 ± 0.535 | -0.157 ± 0.211 | 0.362 ± 0.203 | 0.291 ± 0.162 | 0.071 ± 0.120 |
|         | Rainy  | 0.636 ± 0.399 | 0.573 ± 0.396 | 0.063 ± 0.17 | 0.399 ± 0.248 | 0.428 ± 0.278 | -0.030 ± 0.123 | 0.269 ± 0.158 | 0.216 ± 0.126 | 0.053 ± 0.088 |
|         | Transition | 1.007 ± 0.456 | 0.993 ± 0.474 | 0.014 ± 0.237 | 1.008 ± 0.535 | 1.109 ± 0.611 | -0.101 ± 0.251 | 0.399 ± 0.158 | 0.328 ± 0.145 | 0.078 ± 0.098 |
| DB      | Dry    | 0.568 ± 0.273 | 0.633 ± 0.295 | -0.065 ± 0.163 | 0.754 ± 0.359 | 0.993 ± 0.484 | -0.239 ± 0.178 | 0.427 ± 0.204 | 0.328 ± 0.161 | 0.099 ± 0.117 |
|         | Rainy  | 0.554 ± 0.366 | 0.635 ± 0.44 | -0.080 ± 0.147 | 0.475 ± 0.269 | 0.534 ± 0.306 | -0.059 ± 0.090 | 0.328 ± 0.210 | 0.250 ± 0.145 | 0.078 ± 0.098 |
|         | Transition | 0.783 ± 0.342 | 0.911 ± 0.366 | -0.128 ± 0.135 | 1.017 ± 0.720 | 1.169 ± 0.744 | -0.152 ± 0.271 | 0.364 ± 0.202 | 0.290 ± 0.161 | 0.074 ± 0.120 |
| DT-DB   | Dry    | 0.694 ± 0.334 | 0.674 ± 0.353 | 0.020 ± 0.179 | 0.807 ± 0.450 | 0.964 ± 0.535 | -0.157 ± 0.211 | 0.364 ± 0.202 | 0.290 ± 0.161 | 0.074 ± 0.120 |
|         | Rainy  | 0.636 ± 0.399 | 0.573 ± 0.396 | 0.063 ± 0.17 | 0.399 ± 0.248 | 0.428 ± 0.278 | -0.030 ± 0.123 | 0.269 ± 0.158 | 0.216 ± 0.126 | 0.053 ± 0.088 |
|         | Transition | 1.007 ± 0.456 | 0.993 ± 0.474 | 0.014 ± 0.237 | 1.008 ± 0.535 | 1.109 ± 0.611 | -0.101 ± 0.251 | 0.399 ± 0.158 | 0.328 ± 0.145 | 0.078 ± 0.098 |

*AER: AERONET AODs

Generally, it can be seen that at Nghia Do station, the mean MODIS AODs in the transition period was largest following by that of dry season, and lowest in rainy season (Table 1). This could be the results of two peaks of aerosol loading in March during the dry season and in October during the transition season at Nghia Do station (Fig. 2). This result was similar to the
findings of the other studies [9, 10]. These two peak could be due to the affection of monsoon circulation and biomass burning. In October, stable temperature layer and dry weather, which is the result of North-East monsoon flows in Ha Noi, uplifts the dust in the atmosphere. In addition, heavy cloud and drizzles in March, which is the effect of wind saturated with vapor from the East of China blowing through the Gulf of Tokin, forms the high dense aerosol cloud layers [9]. Moreover, in March and October, the buoyancy force due to the heat flux between the surface and atmosphere in March and October because of surface heating could be one of the factor leading to the high aerosol loading. Furthermore, frequent biomass burning activities during March and October in Viet Nam and Southeast Asia countries [16] could seriously increase the aerosol loading. In addition, the larger average AODs for all MODIS AODs products and AERONET AODs in the dry season than those in the rainy season could be attributed to the heavy rain during the rainy season washing out the PM in the atmosphere which resulting in the reduction of aerosol loading. However, the absolute difference between all MODIS AODs retrievals and AERONET AODs at Nghia Do station in the rainy season were larger than that in the dry season.

Similar to AOD seasonal pattern at Nghia Do station, the MODIS AODs at the Son La station in the transition period and the dry season were larger than the mean AODs in the rainy season due to wash out effect. Moreover, the discrepancy between all MODIS AODs and AERONET AODs at Son La station was higher in the dry season (-0.157 ± 0.211) than those in the rainy season (-0.030 ± 0.123). Additionally, this area is under the strong impact of dry and warm South-West monsoon blowing from Bengal Bay to the continent in March and April. The high temperature, low relative humidity and small rain amount are due to Foehn winds. In addition, the local people activities (cutting tree’s branches in the forest, drying and burning them at field for cultivation) cause high risk of forest fire. Furthermore, high temperature due to strong dry warm Foehn wind heats the land surface, which results in high buoyancy force to elevate the dust to the atmosphere causing dense aerosol layers. Therefore, biomass burning for cultivation and possibly from forest fire adding to the effect of the buoyancy force contribute to very high aerosol loading in March and April at Son La station for all MODIS AOD products and AERONET AODs compared with those in the remaining months (Fig. 2).

The Bac Lieu station is situated in the high density coastal urban area and characterized by Southern climate patterns with two distinct seasons. The dry season is from November to April coinciding with North-East monsoon, while the rainy season is from May to October with the effect of South-West monsoon [17]. Similar to those at Nghia Do and Son La stations, the seasonal mean AODs loading was lowest during the rainy season because of wash out effect (Table 1). Furthermore, the difference between all MODIS AODs retrievals and AERONET AODs at Bac Lieu station in the rainy season was smaller than that in the dry season. Additionally, the North-East monsoons bring the marine aerosol from the sea to the continent [9,10], which could result in the high aerosol loading in dry months. In Bac Lieu, farmers practice three crops per year. Spring crop, autumn crop and winter crop harvested in February to March, August or September, and November or December, respectively. During the harvesting of autumn crops, farmers often leave rice straw residue at field [9]. On the other hand, biomass burning aerosol is observed more frequently in spring and winter crops. Furthermore, the aerosol loading in the middle of the dry season (January to March) is higher than those during the beginning and end months of the dry season. This result can be explained by the fact that the heat flux between the surface and atmosphere does not affect the aerosol loading in Bac Lieu because the surface in Bac Lieu province is heated most of the time in a year.
4. CONCLUSIONS

In this first ever study, the inter-comparison between the C6.1 10 km MODIS AOD and the AERONET AOD was carried out to characterize the deviations between MODIS satellite-based and AERONET ground-based measurements for the urban, coastal urban, and mountainous rural areas in Viet Nam. The inter-compared results showed that none of the product consistently outperforms the others in our studying areas. However, DB AOD product appeared to perform better than DT and DT-DB products in urban area. Additionally, all MODIS products at the coastal area showed worse performances compared to those at the non-coastal areas. Although there were no collocations between the MODIS DB product and the AERONET AOD in August at Bac Lieu station, and in May and September at Son La station, all the MODIS AODs showed their ability to similarly follow the seasonal variation patterns of AERONET AODs. The seasonal mean of MODIS AODs was not only able to capture the peaks of AERONET aerosol loading, but also experienced the similar monthly mean values with those of AERONET data. In addition, in all three investigated stations, aerosol loading in dry season was higher than that in rainy season, which could be attributed to the fact that the rain in wet season washed out the dust and particles in the atmosphere. This study implies that MODIS satellite-based AOD data can be used to complement the existing limited monitoring data from ground-based stations in assessing the surface PM pollution in Viet Nam.

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