Evaluating the potential for application of MODIS satellite data for urban air quality monitoring in Vietnam

B T Hieu, N H Hiep and N D Luong
Faculty of Environmental Engineering, National University of Civil Engineering, 55 Giai Phong Road, Hanoi, Vietnam
E-mail: luongnd1@nuce.edu.vn

Abstract. Using satellite remote sensing data in combining with other technologies (i.e. sensor, ground-based system) for surface air quality monitoring has been considered as one of promising approaches for urban air quality management in future smart cities. This study assessed the accuracy of latest collection (Collection 6.1 - C6.1) of MODerate resolution Imaging Spectroradiometer (MODIS) satellite aerosol optical depth (AOD) retrieval by Dark Target (DT) algorithm at 3 and 10 km spatial resolutions in urban areas in Vietnam. Collocated Aqua and Terra MODIS C6.1 AOD at 550 nm were inter-compared against AOD from two AERONET stations in Vietnam, estimated throughout the satellite passes (± 1 h). Two investigated AERONET stations are Nghia Do (inland urban) and Bac Lieu (coastal urban) with the studying periods of 2010 - 2016 and 2010 - 2017, respectively. Our findings showed that the MODIS DT 3km were performed worse than the MODIS DT 10 km product in urban areas. Furthermore, all two MODIS AOD DT products showed better performance at inland urban site than coastal urban site. In general, both MODIS products were able to follow the monthly-mean AERONET AODs. The peak of aerosol loading at the investigated urban sites could be properly attributed to the combination of the monsoon effect and biomass burning activities. The mean aerosol loading of rainy season appeared to be lowest in the year, which could be attributed to the fact that the frequent rain washes out the dust in the atmosphere.

1. Introduction
Using satellite remote sensing data in combining with other technologies (i.e. sensor, ground-based system) for surface air quality monitoring has been considered as one of promising approaches for urban air quality management in future smart cities. Because of the drawback of the sparse ground monitoring data, which fails to judge the spatio-temporal distribution of air pollutant concentrations at global scale and in developing countries such as Vietnam, different kind of satellites have been launched with the attempt to retrieve Aerosol Optical Depth (AOD). Moderate Resolution Imaging Spectroradiometer (MODIS) provided the most robust and popular AOD to provide information of the aerosols’ effects at both local and global scale. MODIS integrated on Terra and Aqua satellites have launched since 1999 and 2002, respectively to acquire data in 36 spectral bands with the revisit at exact specific location of 1-2 days, and moderate spatial resolutions of 250m, 500m, ad 1000 m. During this time period, National Aeronautics and Space Administration (NASA) continuously
upgraded MODIS AOD retrievals across land at 3 km and 10 km resolutions using dark target (DT) algorithm [1] [2], a 10 km spatial resolution based on the deep blue (DB) algorithm [3], AOD estimated by combination of DT and DB algorithms at 10 km space resolution. Furthermore, satellite retrieved measurements integrated with ground-based measurements could provide multiple-scales environment data, which is required by smart city approach to provide a new and cost-effective method for decision-makers to manage urban air quality [4].

Elevated concentration of air pollutants, especially particulate matter (PM) and its associated health effects due to urbanization and industrialization in the big cities has drawn increasing attention from both policy-makers and scientists in developing countries. Therefore, one of the most popular applications of MODIS AOD products is to produce PM$_{2.5}$ and PM$_{10}$ map from local and national scale for assessing air quality and protecting the environment [5] [6][7][8][9]. Additionally, [10] concluded that the deviation in PM$_{2.5}$ estimation could be the result of the disparity between MODIS AOD products and AOD obtained from the AEROsol Robotic NETwork (AERONET). Furthermore, there have been number of studies worldwide made the comparisons for AODs derived from MODIS and AERONET [11] [12] [13], and their results have shown that the agreements between MODIS and AERONET AODs could deviate from reasonably good to poor, which is contingent upon the aerosol type with the accuracy of retrieval results were different with $\Delta \tau_{\text{land}} = \pm 0.05 \pm 0.20 \tau$ across land [11] and $\Delta \tau_{\text{ocean}} = \pm 0.03 \pm 0.05 \tau$ across ocean [14].

The MODIS DT AODs 3 km has been recently introduced as a fine space resolution AOD in the latest Collection 6.1 with the expectation to make good performances in studying aerosols characteristics and detecting local air pollution [15]. This has tremendous meaning in air quality monitoring, particularly for the highly polluted air environment of developing countries including Vietnam. Although, there is a number of studies validating the MODIS DT AODs products spatially resolved at 3 km and 10 km against the AERONET AODs worldwide [15][16][17][18][19], there has not been any such kind of research in Vietnam. Therefore, our study will bridge these knowledge gaps by evaluating the performances of 3 km and 10 km MODIS AODs products in the newest collection C6.1 for two AERONET stations in Vietnam which representing different climatic zones and different surface types. These stations are Nghia Do and Bac Lieu which are corresponding to the inland urban and coastal urban, respectively. Our study comprehensively assessed the accuracy of MODIS DT AODs 3 km and 10 km space resolution to track monthly-mean AERONET AODs.

2. Material and Methodology

2.1. Study areas

Two AERONET stations (Nghia Do at 105.80 E/21.05 N and Bac Lieu at 105.73 E/9.28 N) located in different climatic zones in Vietnam with different surface types are chosen for studying MODIS aerosol products. The investigated time period of Nghia Do and Bac Lieu were 2010 - 2016 and 2010 - 2017, respectively. Nghia Do AERONET station is situated in a populous urban area in Hanoi, the second biggest city of Vietnam. Hanoi is situated in the North of Vietnam, thus the city has the typical climate of northern of the country. The city experienced a rainy season from May to September, characterized by hot and humid weather with large amount of rainfall. From November to March is dry season, featured by reduction of temperature and precipitation. The transition season starts in April and lasts in October. On the other hand, Bac Lieu is a coastal urban AERONET station situated in the South of Vietnam. The climate of the South features two seasons during a year: rainy and dry season. From May to October is rainy season, and dry season is 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 products are currently the most accurate aerosol data, AERONET AODs can be used as the benchmark to verify MODIS AODs. This study utilized the level 2 DT MODIS AOD products of the newest collection C6.1 at the wavelength of 550 nm with the spatial resolution of 3 km and 10 km. In this study, the MODIS operational aerosol products including DT 3 km and 10 km were achieved from the official website of Atmospheric Archive & Distribution System (LAADS) (https://ladsweb.modaps.eosdis.nasa.gov). With the aim of providing qualified and adequate data, this study employed the level 2.0 AERONET AOD which was achieved from the AERONET homepage (http://aeronet.gsfc.nasa.gov/).

Because AERONET AODs products are currently the most accurate aerosol data, AERONET AODs can be used as the benchmark to verify MODIS AODs. However, the reference AERONET AODs and satellite-retrieved have different spatio-temporal resolutions due to distinct original data sources. Thus, in order to carry out the verification for these two aerosol optical depth datasets, it is required to temporally and spatially collocate the two datasets. Firstly, we only took into account the ground-based and satellite-based AOD which were measured on the same day for matching. For each Terra and Aqua overpass, the mean MODIS AODs over 5 x 5 MODIS Level 2 pixels centred at AERONET site are calculated according to [11]. After matching the ground-based measurements with satellite estimations over the space, the two data set were collocated in time. Because of the substantial variation of the AODs values throughout a single day, it is necessary to collect the satellite-based and ground-based AOD only at comparable times of the day for reasonable comparison. Particularly, the ground-based AOD measurements were averaged within ± 30 min of the satellite overpass time according to the time matching method of [20]. In the next stage, we applied the method mentioned by [19] to convert the ground-based AOD estimations at 0.50 μm to 0.55 μm wavelength using the Ångström exponents values (α) extracted from the AERONET data set.

Linear fitting for MODIS AOD against the AERONET AOD is one of the main method used in this study for validating the quality of MODIS DT AODs at 3 km and 10 km spatial resolution. All of the quantitative parameters (slope, intercept, and R²) are as useful indices of aerosol optical depth at a specific position and time [11]. The correlation between MODIS and AERONET AODs is expressed by the regression coefficient (R²), which is computed as the square of the correlation coefficient. Beside the linear regression analysis, ratio falling inside the expected error (EE) lines 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 Discussions

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 Figure 1, the orange dashed, red solid, and blue dash lines are the 1:1 line, linear regression of the scattering points, and EE range, respectively. MODIS DT AODs 3 km appeared to be less reliable than the 10 km at the urban sites. This finding was consistent with the previous studies which also concluded the greater uncertainties of the 3 km AODs product observed at urban sites than those for the 10 km AODs product [5][6][7][8][9]. The uncertainty of MODIS DT 3 km product appeared to be larger than the MODIS DT 10 km, which could be explained by the larger uncertainty of surface reflectance attributed to keeping of some bright pixels in the retrieved window probably abandoned at 10 km [21].
Figure 1. Validation of MODIS AOD vs. AERONET AOD at two urban stations.

At Bac Lieu station, although the $R^2$ values of the 3 km product was larger than that of the 10 km product, the remaining statistics suggested the better performance of 10 km AODs product than that for 3 km AODs product at this station. The number collocations lying within EE of the 10 km AODs product (51.724%) was higher than that of the 3 km AODs product (only 48.241%), the number of collocations of the 10 km AODs product (435) was higher than that of the 3 km AODs product (398), and the RMB values of the 3 km (1.137) was higher than that of the 10 km product (1.246). At Nghia Do station, although the number of matching inside EE of the two products showed small discrepancy, the remaining statistics indicated that the 3 km AODs product performs poorer than the 10 km AODs product. The number of collocations and the $R^2$ values of the finer spatial resolution product were smaller than those of the coarser one. Although, both MODIS DT AODs products overestimated the aerosol loading, the 10 km AODs product experienced the smaller RMB (1.053) and RMSE (0.195) than those for the 3 km AODs product (1.095 and 0.2 for RMB and RMSE, respectively). The number
of collocations of both MODIS AODs products within EE at two urban stations ranging from 48.241% to 51.724%, which were less than the global validation results [1]. However, this result was comparable with the number of collocations within EE over the Southeast Asia for MODIS DT 10 km of C6 (51%) [10]. The RMSE values at two investigated stations experienced a wide range from 0.137 to 0.241. [11] also reported the RMSE at various AERONET sites in China expressing a wide range from 0.156 to 0.315. In addition, the RMB values of both MODIS DT products at two investigated AERONET stations were in the range of RMB values (from 0.67 to 1.79 and from 0.51 to 1.51 for the 3 km and 10 km products, respectively) at 18 AERONET stations located over China which reported by [9]. The $R^2$ values of the MODIS DT AODs10 km product at Nghia Do and Son La stations (from 0.805 to 0.875) were close to the results of C6 (about 0.88) in China [12] which were substantially higher than the values at Bac Lieu station.

Furthermore, both MODIS DT AODs products expressed the less accuracy at the coastal site compared with those at the inland site with substantially low number of collocations within EE. In addition, the lower $R^2$ values, further RMB values to unity at Bac Lieu coastal site compared with those of non-coastal site also suggested the less reliable performance of MODIS DT products over coastal area. This finding was consistent with the results reported by the other studies [12] [13]. The high RMSE values and low number of collocations within EE at Bac Lieu station were similar to the values over coastal areas reported by [14] (0.154 and 44.7%, respectively). However, the $R^2$ values of both MODIS AODs products at Bac Lieu station were less than the values reported at other coastal sites (about 0.8) [13].

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 Figure 2. The solid green line, dash blue line, and dash-dot yellow line are MODIS data, AERONET data, and disparity between satellite-based and ground-based AODs, respectively.

![Figure 2](image_url)

*Figure 2.* Monthly mean MODIS AOD and AERONET AOD at 550 nm, along with monthly mean of their difference at two urban stations.

It can be seen from Figure 2 that both MODIS AODs products expressed the ability to track the monthly variations of AERONET AODs at two sites. At Nghia Do station, the ranges for AOD
measurements of MODIS DT 3 km and 10 km were from 0.564 ± 0.036 to 1.177 ± 0.041 and from 0.486 ± 0.381 to 1.054 ± 0.588, respectively. Meanwhile, the aerosol loading at Bac Lieu station was relatively lower than that at Nghia Do station with the ranges for MODIS DT 3 km and 10 km were from 0.162 ± 0.085 to 0.447 ± 0.244 and from 0.155 ± 0.05 to 0.462 ± 0.229, respectively. As seen in Table 1, both MODIS DT AODs at Nghia Do station showed the largest mean aerosol in the transition period (0.971 ± 0.397 and 1.007 ±0.456 for the 3 km and 10 km product, respectively) following by that of dry season (0.737 ± 0.370 and 0.695 ±0.335 for the 3 km and 10 km product, respectively), and lowest in rainy season (0.651 ± 0.407 and 0.636 ±0.399 for the 3 km and 10 km product, respectively).

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

| Product | SEASON | NGHIA DO | BAC LIEU |
|---------|--------|----------|----------|
|         | MODIS  | AER(*)   | MODIS-AER | MODIS | AER | MODIS-AER |
| DT 10 km| Dry    | 0.695    | 0.671     | 0.024  | 0.362 | 0.291 | 0.072 |
|         | ±0.335 | ±0.353   | ±0.181    | ±0.203 | ±0.162 | ±0.124 |
|         | Rainy  | 0.636    | 0.573     | 0.063  | 0.269 | 0.216 | 0.053 |
|         | ±0.399 | ±0.396   | ±0.171    | ±0.158 | ±0.126 | ±0.088 |
|         | Transition | 1.007 | 0.993   | 0.014  |        |         |         |
|         | ±0.456 | ±0.474   | ±0.237    |        |         |         |
| DT 3 km | Dry    | 0.737    | 0.667     | 0.071  | 0.374 | 0.284 | 0.091 |
|         | ±0.370 | ±0.354   | ±0.211    | ±0.21  | ±0.1527 | ±0.117 |
|         | Rainy  | 0.651    | 0.578     | 0.073  | 0.305 | 0.236 | 0.068 |
|         | ±0.407 | ±0.383   | ±0.159    | ±0.193 | ±0.133 | ±0.114 |
|         | Transition | 0.971 | 0.931   | 0.041  |        |         |         |
|         | ±0.397 | ±0.433   | ±0.203    |        |         |         |

*AER: AERONET AODs

The relatively higher MODIS DT AODs 3 km and 10 km aerosol loading in transition and dry season could be the results of two peaks of aerosol loading in October during the transition season at Nghia Do station and aerosol loading in March during the dry season (Figure 2). This result was similar to the findings of the other studies [22][23]. The peak of aerosol loading in October could be attributed to the North-East moon soon resulting the stable temperature layer and dry weather which uplifts the dust easily in the atmosphere. The peak of aerosol loading in March could be explained by the high dense aerosol cloud layers which were formed by the wind saturated with vapor from the East of China blowing through the Gulf of Tokin. Beside the monsoon circulation effects, the frequent biomass burning activities during March and October in Vietnam and Southeast Asia countries [24] could seriously increase the aerosol loading. 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 factors leading to the high 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. Furthermore, the mean discrepancy between the MODIS DT 10 km and AERONET AODs at Nghia Do station was consistently smaller than that of the MODIS DT 3 km during 3 seasons which indicated the better performance of the finer spatial resolution product in urban areas. The mean difference between satellite-derived products and
AERONET data of the MODIS DT 3 km were $0.071 \pm 0.211$, $0.073 \pm 0.159$, and $0.041 \pm 0.203$ for dry, rainy, and transition seasons, respectively. Those values of MODIS DT 10 km during dry, rainy, and transition seasons were $0.024 \pm 0.181$, $0.063 \pm 0.171$, and $0.014 \pm 0.237$, respectively.

Similar to those at Nghia Do station, the seasonal mean AODs loading at Bac Lieu station was lowest during the rainy season because of wash out effect (Table 1). In addition, the North-East monsoons bring the marine aerosol from the sea to the continent [22][23], which increases the high aerosol loading in dry months (from November to April). Furthermore, the high aerosol loading in dry season could be the result of burning rice straw residue during spring and winter crops. Moreover, 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. Additionally, similar to the case of Nghia Do urban station, the mean difference during dry and rainy season between the MODIS DT 3 km and AERONET AODs ($0.091 \pm 0.117$ and $0.068 \pm 0.114$, respectively) was stably smaller than that of the MODIS DT 10 km ($0.072 \pm 0.124$ and $0.053 \pm 0.088$, respectively).

4. Conclusions
In this first ever study, the C6.1 3 km and 10 km MODIS DT AOD were validated against the AERONET AOD to analyze the precision and accuracy of satellite-retrieved AODs for the inland urban and coastal urban areas in Vietnam. The inter-compared results showed that the MODIS DT AODs 10 km was more reliable than the 3 km one. Additionally, MODIS products in the coastal urban area showed worse performances compared to those in the inland urban area. Generally, all the MODIS AODs showed their ability to capture the seasonal variation patterns of AERONET AODs. The high aerosol loading values at two urban sites could be attributed to the blending of monsoon effects and burning biomass activities, which requires further study in future. In general, the mean aerosol loading during rainy season experienced lowest values during the year, which could be explained by the fact that the rain would wash out dust suspending 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 the circumstance of elevated air pollution, especially in urban areas in Vietnam. Use of MODIS satellite-based AOD data in combining with other technologies (i.e. low-cost sensor) for surface PM monitoring can be considered as potential approach for urban air quality management for Vietnam’s smart cities in the near future.

Acknowledgements
This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under the grant number 105.08-2017.301. The authors would like to thank the NAFOSTED for providing the financial support for this research. Level 2 MODIS data were provided by Atmosphere Archive and Distribution System (LAADS) at Goddard Space Flight Center (GSFC), (https://ladsweb.modaps.eosdis.nasa.gov/search/). The authors would like to thank the AERONET federation and AERONET scientific team.

References
[1] Levy LA, Remer RC and Munchak LA 2016 Atmos. Meas. Tech. 9 73293–308.
[2] Levy RC, Mattoo S, Munchak LA, Remer LA, Sayer AM, Patadia F and Hsu NC 2013 Atmos. Meas. Tech. 6(11) 2989–3034.
[3] Hsu NC, Jeong MJ, Bettenhausen C, Sayer AM, Hansell R, Sefior CS, Huang J and Tsay CS 2015 J.Geophys.Res.Atmos. 118 9296–315.
[4] Amir A and William GB 2018 Data Analytics for Smart Cities (Boca Raton, Florida: CRC
[5] Chu DA, Kaufman YJ, Zibordi G, Chern JD, Mao J, Li C and Holben BN 2003 J. Geophys. Res. 108 1–18.
[6] Engel-cox JA, Holloman CH, Coutant BW and Hoff RM 2004 Atmos. Environ. 38 2495–509.
[7] Wei You DC, Zang Z, Pan XB and Zhang L 2015 Sci. Total Environ. 505 1156–65.
[8] Yao JWF, Si ML and Li WF 2018 Sci. Total Environ. 618 819-28.
[9] He Q and Huang B 2018 Environ. Pollution. 236 1027–37.
[10] Donkelaar AV, Martin RV, Brauer M, Kahn R, Levy R and Verduzco C 2010 Environ. Health Perspect. 118 847–55.
[11] Ichoku C, Mattoo S, Kaufman YJ, Remer LA, Tanré D, Slutsker I, Holben BN 2002 Geophys. Res. Lett. 29(12) 1–4.
[12] Mhawish A, Banerjee T, Broday DM, Misra A and Tripathi SN 2017 Remote Sens. Environ. 201 297–313.
[13] Holben BN, Eck TF, Slutsker I, Tanré D, Buis JP, Setzer A, Vermote E, Reagan JA, Kaufman YJ, Nakajima T, Lavenu F, Jankowiak I and Smirnov A 1998 Remote Sense. Environ. 66(1) 1-16.
[14] Remer LA, Kaufman YJ, Tanré D, Mattoo S, Chu DA, Martines JV, Li RR, Ichoku C, Levy RC, Kleidman RG and Eck TF 2005 J. Atmos. Sci. 62 947–73.
[15] He Q, Zhang M, Huang B and Tong X 2017 Atmos. Environ. 153 150–62.
[16] Gupta P, Remer LA, Levy RC and Mattoo S 2018 Atmos. Meas. Tech. 11 3145–59.
[17] Shen X and Bilal M 2018 Atmos. Meas. Tech. 11 3145-59.
[18] Munchak LA, Levy RC, Mattoo S, Remer LA, Holben BN, Schafer JS, Hostetler CA and Ferrare R A 2013 Atmos. Meas. Tech. 6(7) 1747–59.
[19] Liu J, Zheng Y, Li Z and Wu R 2018 Atmos. Res. 89 194-205.
[20] Ichoku B, Remer C, Kaufman LA, Levy YJ, Chu R, Tanre’DA and Holben D 2003 J. Geophys. Res. 108(D3) 84–99.
[21] Nichol JE and Bilal M 2016 Remote Sens. 6 328-36.
[22] Tran VT, Pham HV, Nguyen TTN and Pham TX 2018 Land-Atmospheric Research Applications in South and Southeast Asia (Springer Remote Sensing/Photogrammetry. Springer, Cham).
[23] Pham D, Nguyen XT, Pham XA, Do LK, Hoang NT, Nguyen HS and Au XS 2015 Vietnam J. Earth Sci. 37(3) 252–63.
[24] Lasko C, Vadvrevu K, Tran K, Ellicott V, Nguyen E, Bui T and Justice H 2017 Environ. Res. Lett. 12(8) 085006.