STATISTICAL STUDY OF MODIS ALGORITHMS IN ESTIMATING AEROSOL OPTICAL DEPTH OVER THE CZECH REPUBLIC

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ABSTRACT

As a result of the rapid development of remote sensing techniques and accurate satellite observations, it has become customary to use these technologies in ecological and aerosols studies on a regional and global level. In this paper, we analyse the performance of three Moderate Resolution Imaging Spectroradiometer (MODIS) algorithms in estimating Aerosol Optical Depth (AOD) in the Czech Republic to gain knowledge about their accuracy and uncertainty. The Dark Target (DT), the Deep Blue (DB), and the merged algorithm (DTB) of the MODIS latest collection 6.1 Level 2 aerosol products (MOD04_L2) were tested by comparing its results with the measurements of Aerosol Robotic Network (AERONET) Level 3 Version 2.0 ground station at Brno airport. The DT algorithm is compatible the best with AERONET observations with a correlation coefficient (R = 0.823), retrievals falling within the EE envelope (EE% = 82.67%), root mean square error (RMSE = 0.059), and mean absolute error (MAE = 0.044). The DTB algorithm provided close results of the DT algorithm but with less accuracy, on the other hand the DB algorithm has the lowest accuracy between all, but this algorithm was able to provide a bigger sample size than the other two algorithms.

KEYWORDS

AERONET, AOD, DB, DT, DTB, MODIS, Remote sensing

INTRODUCTION

Aerosol Optical Depth (AOD) is a measure of the columnar atmospheric aerosol content, these particles could absorb or scatter the sunlight and prevent it reaching the ground [1]. These small solid or liquid particles are suspended in the atmosphere and they differ in the size, shape, and chemical adaption [2]. Studying of AOD is obtaining more interest day by day, due to its negative impact on all living things by affecting the respiratory system beside reducing naked eye visibility [3]. Humans are not the main cause of aerosols. Aerosols come from many resources like fires, volcanoes, burning of fossil fuels, dust storms and sea drizzles. AOD causes both direct and indirect effects on climate systems according to the lightness or darkness of these particles, in addition to affect the atmospheric radiation energy balance [4]. Deeper and better understanding of aerosol distribution and characteristics is essential for climate change studies [5].

It is not possible to solely rely only on ground observations in estimating AOD, since this process requires a great number of such stations in order to cover all areas, which requires high costs and efforts. For this reason, researches focused on climate changes had to find alternative methods to measure AOD. One of these effective techniques is the Moderate Resolution Imaging Spectroradiometer (MODIS), which is considered the first satellite plan that can provide an accurate information of aerosol optical characteristics. Both the Terra and Aqua satellite platforms have been

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carrying MODIS instrumentations in a sun-synchronous polar orbits, since the year 1999 and 2002, respectively [6]. They are able to record earth's surface with 2330 km viewing swath width every 1 to 2 days [7]. MODIS measures 36 spectral bands between 0.4 and 14.4 μm wavelengths at many different spatial resolutions that provides a great opportunity to study aerosols thickness and parameters characterizing aerosol size from space with good accuracy and on a world-wide scale [8,9], this information helps researchers to estimate AOD loads caused by human-being activities and distinguish it from natural causes [10]. MODIS data has been used to provide useful information on climate changes. Yet, there are many limitations facing satellite aerosol retrieval, including the radiometric calibration, cloud screening, surface reflectance estimation, and aerosol model presumption [11,12]. To get better results from MODIS, several algorithms were designed and developed to use the observed radiances for deriving many important aerosol products. The main purpose of modifying these algorithms is to comply better with the observing instrument specification, properties of aerosols, and nature of clouds [6]. Updated versions of operational aerosol products have been made available over the years, and because of the improvements of these products, we have new datasets collections continuously, starting with collection 4 (C4) to C5, C6, and the latest collection (C6.1) which was released in July 2017.

MODIS Characterization Support Team (MCST) has produced the C6.1 aerosol products, based on the new updated Level 1B calibrated radiance products [13]. Additionally, NASA Ocean Biology Processing Group (OBPG) developed more calibration corrections and these improvements were applied to the MCST top of atmosphere (TOA) products starting with C5 [14,15]. MODIS C6.1 aerosol products have major improvements in both radiometric calibration and all aerosol retrieval algorithms.

MODIS products include many scientific data sets (SDS). In recent updated products, Quality Assurance (QA) dataset is added, which serves as a check point for certain conditions that are to be met during the retrieval process [16]. At the end of the process, QA dataset will provide confidence level; 0 = no retrieval, 1 = poor quality, 2 = moderate quality and 3 = good quality [17]. Since the launch of Terra and Aqua satellites, the Dark Target (DT) algorithm which was proposed by [2] has been applied to the MODIS data. There are two distinct DT algorithms for retrieving AOD, one for retrieving AOD over ocean and the second for retrieving AOD over land. Many improvements were applied to the latest algorithm especially of estimating the model for main urban surfaces [18]. The most common used SDS for the DT algorithm is "Optical-Depth-Land-And-Ocean" it contains only filtered values of AOD retrievals which meet the quality assurance ($QA \geq 1$ over ocean and $QA = 3$ over land) to provide beneficial retrievals over dark areas [19]. By contrast, this algorithm has disadvantages over bright surfaces. For this reason, another algorithm called the Deep Blue (DB) was developed in order to retrieve AOD over bright surfaces like deserts and arid areas [20,21]. Since the releasing of C6, DB has been improved to work affectively over vegetated land surfaces, brighter deserts and urban areas [15]. In the latest C 6.1 DB algorithm was developed from collection 6. It has the following advantages over land, the ability to detect thick smoke, efficient modelling for terrains, and many bug fixes, among others mentioned elsewhere [13]. Beside DB and DT products, there is a merged dataset consists of both DT and DB algorithms (DTB). This merged algorithm works based on the Normalized Difference Vegetation Index (NDVI). According to this methodology, if $NDVI > 0.3$ then the DT algorithm will be applied on the retrievals, if $NDVI < 0.2$ then the DB algorithm will be applied, and if NDVI value is between 0.2 and 0.3 then the combined algorithm of both DT and DB will be applied. DTB dataset offers a better spatial coverage especially for low vegetated areas [19].

To validate the results obtained from MODIS or other satellite sensors, data is usually compared with the measured aerosol parameters of ground-AERONET. A similar regional study by Zawadzka and Markowicz compared the Spinning Enhanced Visible Infrared Radiometer (SEVIRI) data with AERONET observations in Poland and their study showed a good correlation with a root mean square error (RMSE) equals to 0.05 [22]. Based on such comparison, MODIS retrieving algorithms could be further improved to reach a satisfactory outcome [23,24].

DATA DESCRIPTION

MODIS Data

Tow worldwide products are included in the MODIS level-2 daily swath, MxD04-L2 at 10 km resolution and MxD04-3k at 3 km resolution, whereas: x = O for Terra, and x = Y for Aqua. In this study we use the level-2 daily product at 10 km resolution MOD04_L2 of the TERRA satellite, during the period of 18 months (Jun 2017- Dec 2018) over the Czech Republic. Three AOD subset products; DT, DB, and the merged DTB at 550 µm, are generated from the MODIS latest collection C 6.1. All data is publicly available and was downloaded from https://ladsweb.modaps.eosdis.nasa.gov/.

Tab. 1 - Scientific dataset of MODIS used in this study

Product	(SDS) name	Contents	Spatial resolution
MOD04-L2 C6.1	Optical-Depth-Land-And-Ocean	DT over land (QA=3)	10 Km
	Deep-Blue-Aerosol-Optical-Depth-Land-Best-Estimate	DB over land (QA ≥2)	
	AOD-550-Dark-Target-Deep-Blue-Combined	DTB over land and ocean	

AERONET Data

NASA co-sponsors a global network of ground sensors called the Aerosols Robotic Network (AERONET), which is considered as one of the most common and reliable aerosol networks [25]. It is a multi-channel instrument that takes automatic measurements for both direct solar irradiance and sky radiance at the Earth's surface. AERONET takes observations of the solar radiation at seven wavelengths (380, 440, 500, 675, 870, 936 and 1020 nm) around every 15 minutes with low uncertainty ranging between (0.01-0.02) under cloud-free conditions [26]. The AOD is retrieved from these channels to provide high accuracy and quick results. The latest version of AERONET is version three (V3) level two (L2.0) which is computed for three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened and quality controlled), and Level 2.0 (quality-assured). Inversions, precipitable water, and other AOD-dependent products are derived from these levels [27]. In the Czech Republic there is only one AERONET station. This AERONET CIMEL instrument has approximately 1.2° full angle field of view (FOV) and it is installed on the roof of the administrative building in Brno Airport (Figure 1) at the following coordinates: latitude 49.15647º N, longitude 16.68333º E, and with an elevation of 238 m above sea level, this station can observe and process the data automatically, and it is calibrated yearly to provide the best results, and to avoid offsets occurrence in the radiance measurements [28].

In this study, we present data from level 2.0 of the data quality assurance. AERONET AOD measurements at 440 μm and 675 μm from Brno Airport station during the period (June 2017 – December 2018). These observations were interpolated to 550 nm, in order to compare it with MODIS retrievals, using the Angstrom exponents (440 – 675 μm) provided in the AERONET datasets according to the Angstrom's turbidity equation [29] represented in Equation (1).

$$\tau_a(\lambda) = \beta\lambda^{-\alpha} \tag{1}$$

The AOD values at two different wavelength values λ_1, λ_2 are related by Equation (2).

$$\tau_a(\lambda_1) = \tau_a(\lambda_2) * \left(\frac{\lambda_1}{\lambda_2}\right)^{-\alpha} \tag{2}$$

where $\tau_a(\lambda)$ is the AOD at a wavelength λ in microns, α is the Angstrom wavelength exponent, and β is the Angstrom's turbidity coefficient.

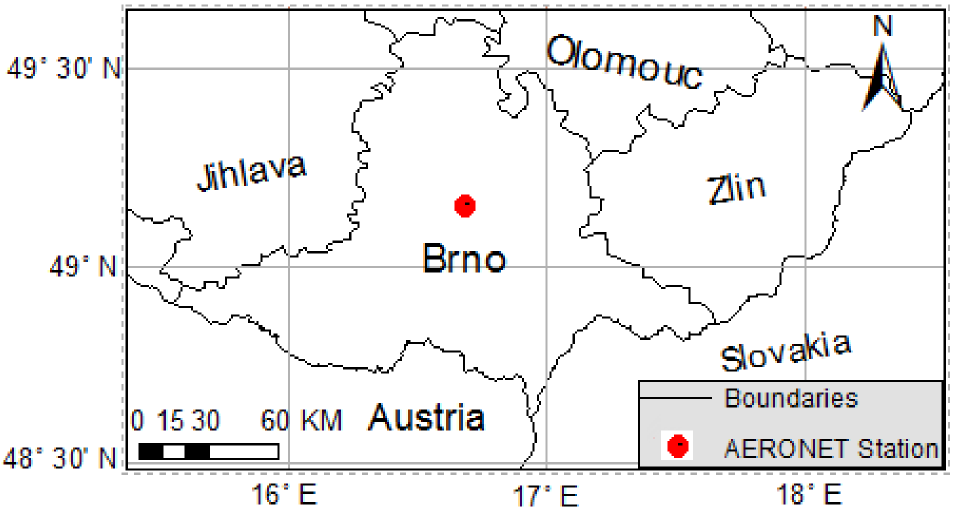

Fig. 1 – Geographical boundaries of the area of study. The red dot represents the location of the AERONET station.

METHODOLOGY

The comparison takes place between the average of Brno AERONET observations in the period (± 30 minutes) of the Terra satellite passing over this station (approximately 10:30 am), and the mean value of AOD retrievals at 550 μm of nine-pixel sample centered on this AERONET station, at least three pixels should be available and have the required quality assurance, QA=2,3 for DB, and QA=3 for DT and DTB. Considering that AODAERONET represents the true value [30]. To determine the uncertainty of retrieving algorithms with a sample size (N) versus AERONET measurements, we calculate the Pearson product-moment correlation coefficient (R), RMSE, shown in Equation (3), and the Mean Absolute Error (MAE) as presented in Equation (4), to find which algorithm is compatible the best with the ground observations. Moreover, we will use the Expected Error (EE) equation for retrieving AOD over land at the 10 km spatial resolution [31] to determine the quality of retrievals, the EE equation is represented in Equation (5). Retrievals falling within the EE envelopes must meet Equation (6).

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum(AOD_{AERONET} - AOD_{MODIS})^2} \qquad (3)$$

$$\mathrm{MAE} = \frac{1}{N}\sum|\, AOD_{AERONET} - AOD_{MODIS}\,| \qquad (4)$$

$$\mathrm{EE} = \pm\,(0.05 + 0.15 \times \mathrm{AODAERONET}) \qquad (5)$$

$$\mathrm{AOD_{AERONET}} - |\mathrm{EE}| \leq \mathrm{AOD_{MODIS}} \leq \mathrm{AOD_{AERONET}} + |\mathrm{EE}| \qquad (6)$$

RESULTS AND DISCUSSION OF VALIDATION AND COMPARISON WITH AERONET OBSERVATIONS

After downloading and processing MODIS data, only data satisfying QA requirements corresponding to each algorithm in question were used during the study analysis.

Figure 2 shows the validations of Terra C6.1 DB, DT, and DTB retrievals compared to AERONET AOD measurements at the Brno Airport site from June 2017 to December 2018 (18 months). During the retrieval process, we noticed that the least number of retrievals were obtained from winter months due to thick cloud and snow coverage. According to data analysis, the C6.1 DT AOD retrievals agrees the best with AERONET AOD measurements (R = 0.823), and the percentage of retrievals falling within the EE envelope is remarkably high (82.67%), with an average Mean Absolute Error (MAE = 0.044) and the smallest root mean square error compared to the other algorithms (RMSE = 0.059). DB has the lowest correlation coefficient (R = 0.765), also the error was noticeably high with (RMSE = 0.069 and MAE = 0.052). On the other hand, the DB has a slightly better percentage of data samples that fell within the EE envelope than the DTB retrievals with EE (80.85%) and (80%) respectively. Moreover, DTB retrievals show better results than DB retrievals (R = 0.819), and the error is slightly higher than that of DT retrievals (MAE = 0.047 and RMSE = 0.063). Figure 3 shows the linear regression between each MODIS algorithm retrievals and AERONET observations, it also shows the real error ($\tau_{MODIS} - \tau_{AERONET}$) for each pair of AOD. According to Figure 3, we found that the errors of all three algorithms have normal distribution on both sides of the 1:1 line with close proportions. Besides that, almost all retrievals of the three algorithms with low values of AOD (AOD < 0.1) have small errors. Based on obtained results, we found that the DTB (Figure 3c) was more influenced by the DT (Figure 3b) than DB (Figure 3a). Besides, the sample size for both algorithms was the same (N = 75) since the required QA value for both the DT and DTB algorithms is 3. DT algorithm alone gave good results. This is of no surprise, as the DT algorithm is known to be suitable for highly vegetated areas, such as the Czech Republic. According to Wie et al, the DT is more suitable for highly vegetated and low AOD loading areas in all Europe, which is consistent with our findings [13]. However, one drawback for this algorithm might be the sample size as larger sample size and probably larger coverage area can be obtained by the DB algorithm due to lower QA requirement (QA = 2 or 3). One challenge that faced us during this study is the fact that there is only one AERONET station in the Czech Republic located in Brno. Even this station was under calibration and data from three months (June – August, 2018) was missing. However, by merging the data from the years 2017 and 2018 we were able to have MODIS AOD retrievals from the four seasons and increase the reliability of the validation.

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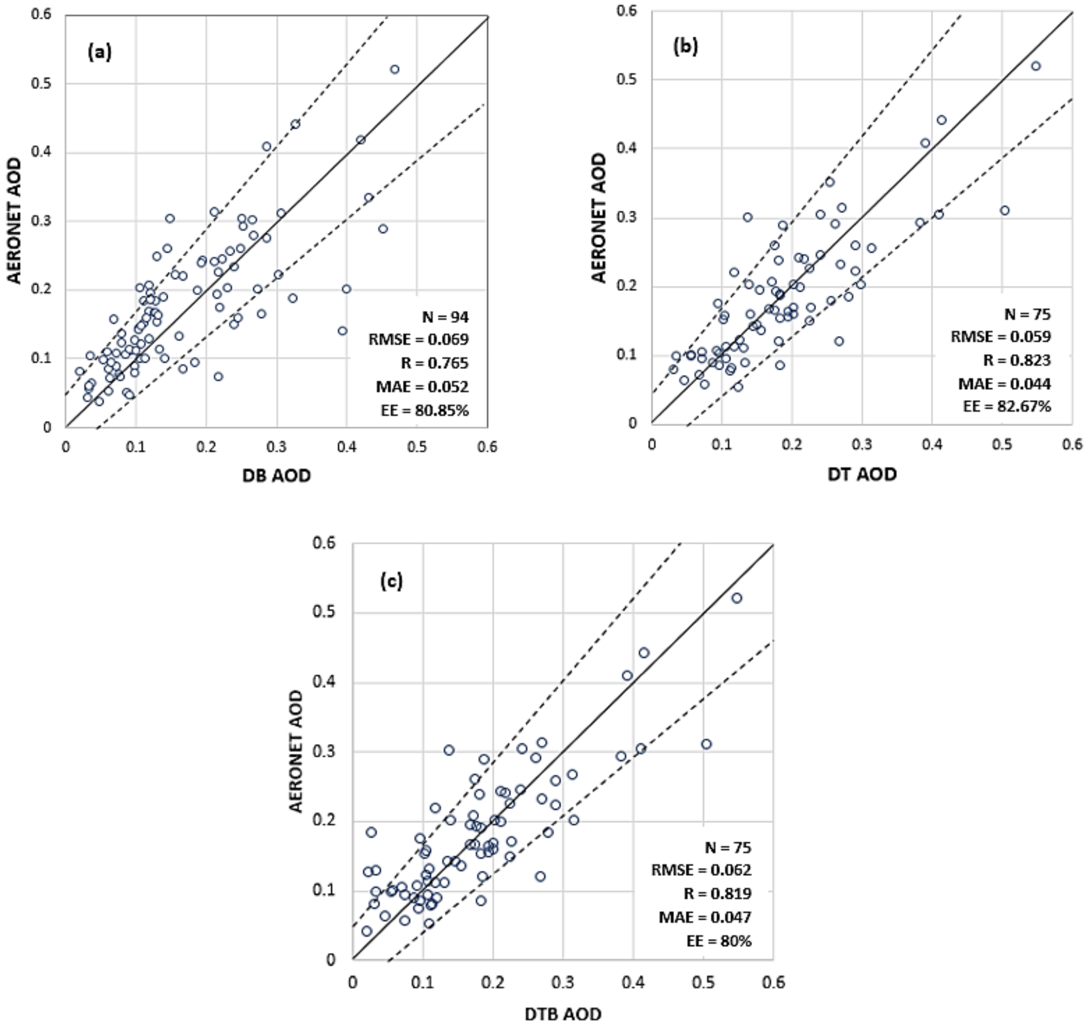

Fig. 2 – *Scatter plots of Terra MODIS C6.1 DB (a), DT (b) and DTB (c) AOD retrievals against AERONET AOD observations from June 2017 to December 2018. The solid line indicates the 1:1 line, and the dashed lines indicates the envelopes of the expected error (EE). The sample size (N), correlation coefficient (R), mean absolute error (MAE), and root-mean-square error (RMSE) are also given. EE represent the percentages (%) of retrievals falling within the EE envelopes.*

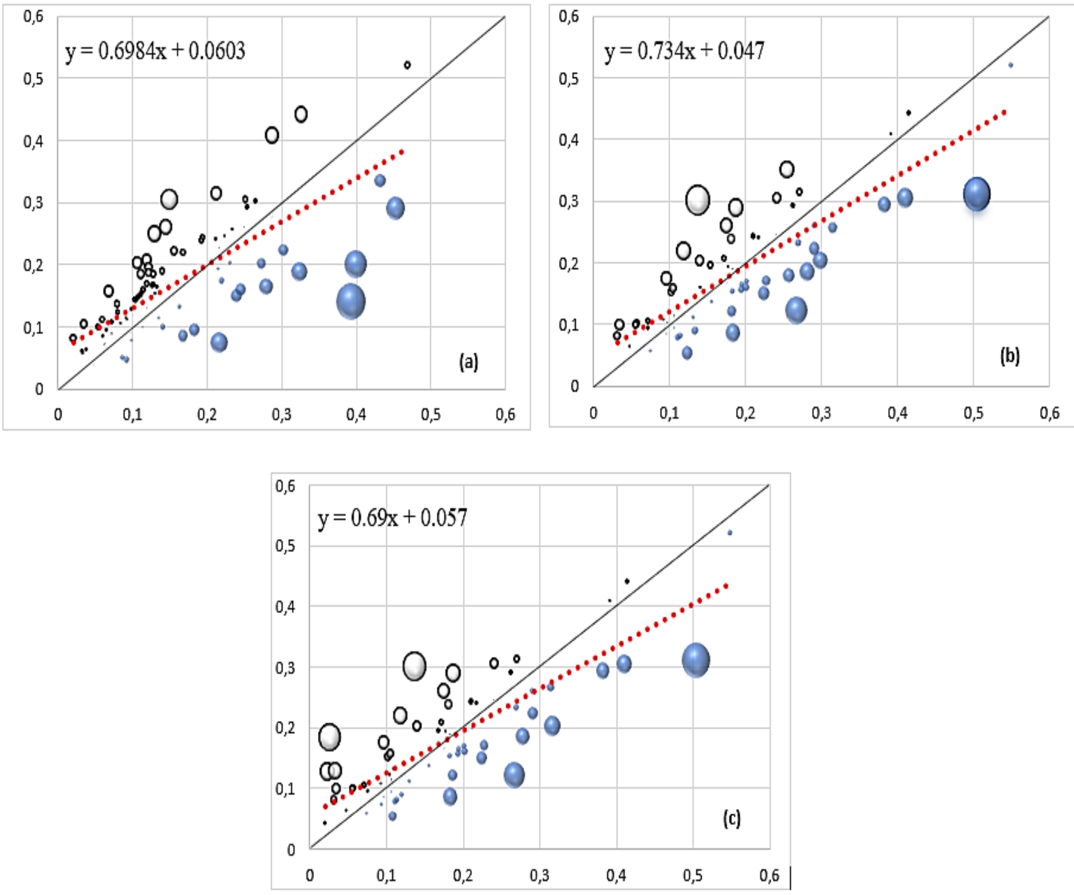

Fig. 3 – *The linear regression between MODIS C6.1 DB (a), DT (b), and DTB (c) AOD retrievals against AERONET AOD observations. The X axis represents MODIS retrievals and the Y axis represents AERONET observations. The solid line indicates the 1:1 line. Each circle represents one pair of MODIS/AERONET AOD, and its size is based on the value of the real error. The blue circles represent the pairs of AOD when (τMODIS > τAERONET) and white circles represent the pairs when (τAERONET > τMODIS).*

SUMMARY AND CONCLUSION

Three AOD products; DB, DT, and DTB, generated from MODIS C6.1, were compared and validated over land at Brno AERONET station (version 3 Level 2) in the Czech Republic during the period (June 2017 till the end of 2018). We investigated the accuracy and uncertainty of the three algorithms in order to draw recommendations. Based on our results, the DT algorithm gave the closest estimations to the real AOD values observed at Brno AERONET station, with a correlation coefficient (R = 0.823), root mean square error (RMSE = 0.059), and with a high percentage of retrievals falling within the EE envelope (EE = 82.67%). The combined algorithm, DTB, failed to bring better estimations than the DT algorithm alone, yet it was found to be more suitable than the use of the DB algorithm solely. The accuracy of the DB was lower than the other two algorithms, yet still acceptable for estimating AOD as 80.85% of retrievals fell within the expected error envelope. We also found that the MODIS coverage is highly effected by NDVI, among other factors like snow surfaces and cloud density, and thus we recommend testing the coverage of the three MODIS algorithms above all the Czech Republic first and then use the results of the current study to reach an optimal methodology to estimate the AOD over the whole country. Another recommendation would be using the AERONET data of 2019 when it is fully available to investigate whether a longer period influences the results of the current statistics study.

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