Global Validation of MODIS C6 and C6.1 Merged Aerosol Products over Diverse Vegetated Surfaces

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Abstract: In this study, the MODerate resolution Imaging Spectroradiometer (MODIS) Collections 6 and 6.1 merged Dark Target (DT) and Deep Blue (DB) aerosol products (DTB C6 and DTB C6.1) at 0.55 µm were validated from 2004–2014 against Aerosol Robotic Network (AERONET) Version 2 Level 2.0 AOD obtained from 68 global sites located over diverse vegetated surfaces. These surfaces were categorized by static values of monthly Normalized Difference Vegetation Index (NDVI) observations obtained for the same time period from the MODIS level-3 monthly NDVI product (MOD13A3), i.e., partially/non–vegetated (NDVI P ≤ 0.3), moderately–vegetated (0.3 < NDVI M ≤ 0.5) and densely–vegetated (NDVI D > 0.5) surfaces. The DTB C6 and DTB C6.1 AOD products are accomplished by the NDVI criteria: (i) use the DT AOD retrievals for NDVI > 0.3, (ii) use the DB AOD retrievals for NDVI < 0.2, and (iii) use an average of the DT and DB AOD retrievals or the available one with highest quality assurance flag (DT: QAF = 3; DB: QAF ≥ 2) for 0.2 ≤ NDVI ≤ 0.3. For comparison purpose, the DTB SMS AOD retrievals were included which were accomplished using the Simplified Merge Scheme, i.e., use an average of the DT C6.1 and DB C6.1 AOD retrievals or the available one for all the NDVI values. For NDVI P surfaces, results showed that the DTB C6 and DTB C6.1 AOD retrievals performed poorly over North and South America in terms of the agreement with AERONET AOD, and over Asian region in terms of retrievals quality as the small percentage of AOD retrievals were within the expected error (EE = ± (0.05 + 0.15 × AOD). For NDVI M surfaces, retrieval errors and poor quality in DTB C6 and DTB C6.1 were observed for Asian, North American and South American sites, whereas good performance, was observed for European and African sites. For NDVI D surfaces, DTB C6 does not perform well over the Asian and North American sites, although it contains retrievals only from the DT algorithm which was developed for dark surfaces. Overall, the performance of the DTB C6.1 AOD retrievals was significantly improved compared to the DTB C6, but still more improvements are required over NDVI P, NDVI M and NDVI D surfaces of Asia, NDVI M and NDVI D surfaces of North America, and NDVI M surfaces of South America. The performance of the DTB SMS retrievals was better than the DTB C6 and DTB C6.1 retrievals with 11–13% (31%) greater number of coincident observations, 6–9% (14–22%) greater percentage of retrievals within the EE, and 30–100% (46–100%) smaller relative mean bias compared to the DTB C6.1 (DTB C6) at a global scale.

Keywords: AERONET; MOD04; AOD 550 nm; DT; DB; Merged AOD 550 nm
1. Introduction

The MODerate resolution Imaging Spectroradiometer (MODIS) is operating on both the Terra and Aqua spacecraft. It provides extensive geophysical data set for every 1 to 2 days at three spatial resolutions of 250 m, 500 m, and 1000 m for 36 spectral wavelengths from 0.4 to 14.4 \( \mu \)m. The MODIS aerosol product provides daily observations of Aerosol Optical Depth (AOD) at global scale over vegetated (dark) land [1–3] and ocean surfaces [2,4] based on the Dark Target (DT) land and DT ocean algorithms, receptively, and over bright land surfaces based on the Deep Blue (DB) algorithm [5–7]. The collection 6 (C6) of MODIS level-2 operational aerosol products for Terra (MOD04) and Aqua (MYD04) includes a new Scientific Data Set (SDS) “AOD_550_Dark_Target_Deep_Blue_Combined” which represents the merged aerosol product (DTB\(_{C6}\)) based on the DT and DB aerosol retrieval algorithms [2,8].

For the C6 DT algorithm, pixels at 500 m resolutions are selected for dark vegetated surfaces using the top of atmosphere reflectance (TOA) between 0.01 and 0.25 and corrected for gas absorption. The selected pixels are organized into 400 pixels’ boxes (20 × 20 pixels) for cloud mask, and removal of snow/ice and other bright surfaces as the DT\(_{C6}\) algorithm does not perform aerosol retrievals over these surfaces. The 0.66 \( \mu \)m channel is used to separate land and water pixels, and discarding the 20\% darkest and the 50% brightest pixels from the retrieval boxes. From the remaining pixels, more than 50 out of 120 pixels (remaining pixels after 70\% exclusion from the original 400) are required to perform aerosol retrievals for highest quality assurance flag (QAF = 3), and for QAF = 2, 1, 0, more than 30, 20 and 12 pixels are required, respectively. The expected error (EE) of the DT algorithm over land is \( \pm (0.05 + 0.15 \times \text{AOD}_{\text{AERONET}}) \) [2]. The EE represents a one standard deviation confidence interval around the retrieved AOD, i.e., about 68\% of points should fall within \( \pm \)EE from the true AOD, and validation studies suggest that this is met on global average [8,9]. Recently, the Collection 6.1 (C6.1) DT\(_{C6.1}\) aerosol product has been released, and modifications made for C6.1 over land compared to C6 are: (i) the quality of AOD retrievals degraded to zero if more than 50\% coastal pixels or 20\% of water pixels are within 400 pixels’ boxes (20 × 20 pixels), and (ii) the surface reflectance ratios for urban area were revised using MODIS operational surface reflectance product (MOD09) as described in [10]. List of modifications in the DT\(_{C6.1}\) algorithm is available at https://modis-atmosphere.gsfc.nasa.gov/sites/default/files/ModAtmo/C061_Aerosol_Dark_Target_v2.pdf.

For the C6 DB algorithm, pixels at 1 km spatial resolution are masked for clouds and snow/ice surfaces, and the remaining pixels are used to calculate surface reflectance at the 0.412, 0.470, and 0.650 \( \mu \)m channels using (i) the dynamic surface reflectance [5], or (ii) a pre-calculated surface reflectance database, or (iii) a combination of these two methods. The selection of one of these methods depends on the TOA reflectance in the 2.1 \( \mu \)m and the Normalized Difference Vegetation Index (NDVI). The DB algorithm retrieves AOD at 1 km spatial resolution over dark, as well as bright urban and desert surfaces, and then aggregates the retrievals to 10 km spatial resolution. The EE for DB is dependent on the geometry but is approximately 0.03 + 0.20 on average (i.e., the algorithms have different error characteristics) [2,5]. The newly released DB\(_{C6.1}\) aerosol product made modifications in the algorithm compared to C6 which are: (i) artifacts in heterogeneous terrain were reduced, (ii) surface reflectance modelling for elevated terrain was improved, (iii) regional/seasonal aerosol models were updated, (iv) metadata was updated especially for Ångström Exponent, (v) EE was updated, and (vi) internal smoke detection masks were improved. List of modifications made for the DB\(_{C6.1}\) algorithm is available https://modis-atmosphere.gsfc.nasa.gov/sites/default/files/ModAtmo/modis_deep_blue_c61_changes2.pdf. In this study, the EE for DT algorithm is used for all calculations.

In C6 and C6.1, the new DT and DB merged (DTB\(_{C6}\) and DTB\(_{C6.1}\)) AOD products are based on the DT and DB AOD retrievals, and the DT and DB algorithms have different spatial coverage of AOD retrievals over land due to differences in their approaches, i.e., selection of pixels, surface reflectance estimation method, and cloud mask. The purpose of this new product is to increase the spatial coverage of AOD retrievals over land while preserving the quality of the retrievals [2,8], i.e., to retrieve AOD in the same image for those regions where the DT algorithm does not retrieve due to thresholds based on
visible–infrared channels, and cloud mask [2], and where the DB algorithm does not retrieve due to a more stringent cloud mask than DT which more often erroneously removes cloud-free pixels [5,11]. The DTB_C6 and DTB_C6.1 AOD products are accomplished by the NDVI criteria [2]: (i) use the DT AOD retrievals for NDVI > 0.3, (ii) use the DB AOD retrievals for NDVI < 0.2, and (iii) use an average of the DT and DB AOD retrievals or the available one with highest quality assurance (DT: QAF = 3; DB: QAF ≥ 2) for 0.2 ≤ NDVI ≤ 0.3. The newly released DTB_C6.1 AOD product is based on the same approach as the DTB_C6, but the modifications in DT_C6.1 and DB_C6.1 AOD retrievals make it different than the DTB_C6.

Recently, Bilal et al. [9] have introduced three new methods to improve the spatiotemporal coverage and reduce the errors in the DTB_C6 merged aerosol product. These methods were validated against AERONET sites located on mixed surfaces and compared with the DTB_C6. This study concluded that the DTB_SMS (DTB_M1 in [9]) method, which is based on the Simplified Merge Scheme (SMS), is robust over mixed surfaces as (i) it is independent of NDVI, (ii) increases the number of coincident observations, (iii) reduces the RMSE, and (iv) increases the percentage of retrievals within the EE compared to the other proposed methods in [9] and DTB_C6, and therefore, recommended to use operationally at a global scale. The DTB_C6, DTB_C6.1, and DTB_SMS AOD retrievals have not been validated yet at regional to global scales for AERONET sites located over diverse vegetated surfaces or over surfaces with the same NDVI values. Therefore, the objective of this study is to validate the DTB_C6, DTB_C6.1, and DTB_SMS AOD retrievals over diverse vegetated surfaces, i.e., partially/non–vegetated surfaces (NDVI_p ≤ 0.3), moderately–vegetated surfaces (0.3 < NDVI_m ≤ 0.5) and densely–vegetated surfaces (NDVI_d > 0.5) against 68 AERONET sites at regional to global scales from 2004–2014. The present study is different than the previous one [9], as first, land surfaces are categorized based on the NDVI values, and then, AOD observations obtained from DTB_C6, DTB_C6.1 and DTB_SMS were validated against AERONET sites located over diverse vegetated surfaces. A complete list of abbreviations used in the manuscript is provided in Appendix A.

2. Dataset

In this study, Terra MODIS C6 and C6.1 level-2 operational aerosol products (MOD04) at 10 km spatial resolution were downloaded from “the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC)” (https://ladsweb.modaps.eosdis.nasa.gov/) at global scale to obtain the DTB_C6, DT_C6.1, the DB_C6.1, and the DTB_C6.1 AOD retrievals from 2004 to 2014. MODIS C6 monthly level-3 Normalized Difference Vegetation Index (NDVI) product (MOD13A3) was downloaded to categorize diverse vegetated surfaces. For validation of satellite AOD retrievals, AERONET [12–15] Version 2 Level 2.0 (cloud–screened and quality–assured) [16] AOD data were downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov) for all the 68 sites and the respective time periods. The detailed summary of the data set is provided in Table 1, and list of AERONET sites used in this study is given in Table 2.

Table 1. Summary of data set used in the current study.

| Data Scientific Data Set (SDS) | Contents |
|-------------------------------|----------|
| AERONET                        | Version 2 Level 2.0 AOD |
| MOD04 C6/C6.1                 | Optical_Depth_Land_And_Ocean AOD of QAF = 3 over land and QAF = 1 to 3 over ocean |
| Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate | AOD of QAF ≥ 2 over land |
| AOD_550_Dark_Target_Dark_Blue_Combined | AOD of QAF = 1 to 3 over land and ocean |
| AOD_550_Dark_Target_Dark_Blue_Combined_QAF_Flag | QAF = 1 to 3 |
| MOD13A3                       | 1 km NDVI | Monthly NDVI |
Table 2. List of AEROENT sites used in this study.

| Site Name | Lat. (°N) | Long. (°E) | Site Name | Lat. (°N) | Long. (°E) |
|-----------|-----------|------------|-----------|-----------|------------|
| **African Sites** | | | | | |
| CRPSM Malindi | −2.9960 | 40.1940 | Pretoria CSIR | −25.7570 | 28.2600 |
| Gorongosa | −18.9780 | 34.3510 | Skukuza | −24.9920 | 31.5870 |
| ICIPE-Mbita | −0.4170 | 34.2000 | Wits University | −26.1920 | 28.0290 |
| **Asian Sites** | | | | | |
| Beijing | 39.9770 | 116.381 | Nha Tran | 12.2050 | 109.21 |
| Chiang Mai Met Sta. | 37.1710 | 98.9720 | Pune | 18.5370 | 73.8050 |
| Jaipur | 26.9060 | 75.8060 | SKLPM | 15.2460 | 100.0410 |
| Kanpur | 26.9060 | 80.3200 | Ubon Ratchathani | 15.2460 | 104.8710 |
| NGHIA_DO | 21.0480 | 105.8000 | | | |
| **European Sites** | | | | | |
| Arcachon | 44.6640 | −1.1630 | Leipzig | 51.3520 | 12.4350 |
| Aubiere LAMP | 45.7610 | 3.1110 | Lille | 50.6120 | 3.1420 |
| Avignon | 45.9330 | 4.8780 | Minsk | 53.9200 | 27.6010 |
| Brusel | 50.7830 | 4.350 | Moscow MSU MO | 55.7000 | 37.5100 |
| Cabau | 51.9710 | 4.9270 | Munich University | 45.1480 | 11.5730 |
| Carpentras | 44.0830 | 5.0850 | OHP OBSERVATOIRE | 43.9350 | 5.710 |
| Chibolton | 51.1440 | −1.4370 | Palaiseau | 48.7000 | 2.2080 |
| Granada | 37.1640 | −3.6050 | Paris | 48.8670 | 2.3330 |
| Hamburg | 53.5680 | 9.9730 | Rome Tor Vergata | 41.8400 | 12.6470 |
| Ispra | 45.8030 | 8.6270 | Toravere | 58.2550 | 26.4600 |
| Kanzelhohe Obs. | 46.6780 | 13.9070 | TUBITAK UZAY Ankara | 39.8910 | 32.7780 |
| **North American Sites** | | | | | |
| Ames | 42.0210 | −93.7750 | GSFC | 38.9920 | −76.8400 |
| Appalachian State | 36.2150 | −81.6940 | Harvard Forest | 42.5320 | −72.1880 |
| Bilerica | 42.5280 | −71.2690 | KONZA EDC | 39.1020 | −96.6130 |
| BONDVILLE | 40.0530 | −105.0850 | Sevilleta | 34.3550 | −106.8850 |
| Bozeman | 45.6620 | −111.0450 | Sioux Falls | 43.7860 | −96.2620 |
| Dayton | 39.8770 | −118.1250 | TABLE MOUNTAIN CA | 34.3800 | −117.6800 |
| Frenchman Flat | 36.8090 | −115.9350 | Tucson | 32.2330 | −119.5300 |
| Fresno | 36.7820 | −119.7730 | UCSB | 34.4150 | −119.8450 |
| Georgia Tech | 33.7800 | −84.4050 | Univ. of Houston | 29.7180 | −95.3420 |
| Grand Forks | 47.9120 | −97.3250 | | | |
| **South American Sites** | | | | | |
| Alta Floresta | −9.8710 | −56.1040 | CUIABA-MIRANDA | −15.7290 | −56.0210 |
| Campo Grande SONDA | −20.4380 | −54.3580 | Manaus EMBRAPA | −2.8910 | −59.9700 |
| CASLEO | −31.7990 | −69.3060 | Rio Branco | −9.9570 | −67.8690 |
| CEILAP-BA | −34.5670 | −58.3000 | Sao Martinho SONDA | −29.4430 | −53.8230 |

3. Methods

In this study, the DTB\textsubscript{C6}, DTB\textsubscript{C6.1}, and DTB\textsubscript{SMS} AOD retrievals were validated against 68 AERONET sites located over diverse vegetated surfaces in Asia, Europe, Africa, North and South America from 2004 to 2014. The methodology of this study is based on the following steps:

(i) The DTB\textsubscript{C6} and DTB\textsubscript{C6.1} AOD retrievals were obtained from the SDS “AOD\_550\_Dark\_Target\_Deep\_Blue\_Combined” which were filtered for highest quality assurance flag (QAF = 3) using the SDS “AOD\_550\_Dark\_Target\_Deep\_Blue\_Combined\_QA\_Flag”.

(ii) For the DTB\textsubscript{SMS}, the DT\textsubscript{C6.1} highest quality assurance flag (QAF ≥ 3) AOD retrievals were obtained from the SDS “Optical\_Depth\_Land\_And\_Ocean” and the DB\textsubscript{C6.1} highest quality assurance flag (QAF ≥ 2) AOD retrievals were obtained from the SDS “Deep\_Blue\_Aerosol\_Optical\_Depth\_550\_Land\_Best\_Estimate”. The DTB\textsubscript{SMS} product is generated by Simplified Merge Scheme (SMS) [9,17], i.e. “use an average of the DT\textsubscript{C6.1} and DB\textsubscript{C6.1} AOD retrievals or the available one for all the NDVI values [9]” which is independent of NDVI.

(iii) AERONET measurements do not provide AOD data at 0.55 μm, therefore, AOD data were interpolated to 0.55 μm using Ångström exponent 440–675 nm (\(\alpha_{440–675}\)) [11].
(iv) To increase temporal coverage of AOD data, retrievals were defined as the average of at least two pixels of DTBC6/DTC6.1/DTBMS within a spatial region of $3 \times 3$ pixels (at least 2 out of 9 pixels) centered on the AERONET site and the average of at least two AERONET AOD measurements between 10:00 and 12:00 local solar time.

(v) The DTBC6, DTC6.1, and DTBMS AOD retrievals were filtered for three diverse types of land surfaces, i.e., partially/non-vegetated ($\text{NDVI}_P \leq 0.3$), moderated-vegetated ($0.3 < \text{NDVI}_M \leq 0.5$) and dense-vegetated ($\text{NDVI}_D > 0.5$) surfaces defined by static values of monthly NDVI observations obtained from the MOD13A3 C6 L3 product. Bilal and Nichol [18] found that dynamic values of NDVI can improve the accuracy of the DTBC6 AOD retrievals, but in this study, static values of NDVI were used as the DTBC6 and DTC6.1 products are based on these values [2,8].

(vi) The errors and quality of the retrievals were reported using the relative mean bias (RMB, Equation (1)), root mean square error (RMSE, Equation (2)), and the expected error (EE, Equation (3)) of the DT algorithm over land. To compare different methods statistically, the percent relative differences in N, R, EE, RMSE, and RMB R are calculated using Equation (4)

\[
\text{RMB} = \left( \frac{\text{AOD} \text{(MODIS)} - \text{AOD} \text{(AERONET)}}{\text{AOD} \text{(AERONET)}} \right) \tag{1}
\]

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \text{AOD} \text{(MODIS)}_i - \text{AOD} \text{(AERONET)}_i \right)^2} \tag{2}
\]

\[
\text{EE} = \pm \left( 0.05 + 0.15 \times \text{AOD} \text{(AERONET)} \right) \tag{3}
\]

\[
\% \text{ Relative Difference} = \left( \frac{\text{DTBC6.1} - \text{DTBMS}}{\text{DTBC6.1}} \right) \times 100 \tag{4}
\]

4. Results

To point out an efficient and robust aerosol product among the DTBC6, DTC6.1, and DTBMS, the following criteria [8,9] are used in the following sections: if either of the product has relative difference using Equation (4) greater than (i) 5% for the coincident observations (N), (ii) 5% for the percentage of retrievals within the EE, (iii) 5% for the correlation coefficient, and less than (iv) 5% for the RMSE and RMB, then it will be considered to perform best over the specific surface type and region.

4.1. Validation of DTBC6, DTC6.1, and DTBMS AOD over Diverse Vegetated Surfaces at Regional Scale

4.1.1. Validation of AOD Retrievals over Diverse Vegetated Surfaces of Asia

Validation of the DTBC6, DTC6.1, and DTBMS AOD retrievals was conducted over 9 Asian sites (Table 2) located at diverse vegetated surfaces (Figure 1). In Figure 1, the dashed lines represent the EE envelope and the solid line has a slope of unity. The large numbers of AOD measurements from AERONET were available for NDVI$_M$ surfaces ($N = 4485$) followed by NDVI$_P$ surfaces ($N = 2933$) and NDVI$_D$ surfaces ($N = 726$). These AOD measurements for NDVI$_P$ and NDVI$_M$ surfaces were available from January to December and for NDVI$_D$ surfaces were available from June to November. AERONET has large numbers of AOD measurements for NDVI$_M$ surfaces, whereas, the DTBC6 product has 31.91% and 27.02% more retrievals over NDVI$_P$ surfaces ($2465/2933 \times 100 = 84.04\%$) (Figure 1a) than the NDVI$_M$ (Figure 1b: 52.13%) and NDVI$_D$ (Figure 1c: 57.02%) surfaces, respectively. The DTBC6 AOD retrievals have correlation coefficient $\geq 0.88$ for all the surfaces, whereas the retrievals were performed well over NDVI$_M$ surfaces as the large percentage of retrievals (63%) were within the EE for these surfaces compared to the NDVI$_P$ (51%) and NDVI$_D$ (51%) surfaces. This was also supported by low
RMB (0.11) for NDVI$_M$ surfaces which were 35% and 61% lower than RMB for NDVI$_P$ (0.17) and NDVI$_D$ (0.28) surfaces, respectively.

For DTB$_{C6.1}$, fraction of observations coincident with AERONET was 91.58% for the NDVI$_P$ surfaces (Figure 1d), 70.61% for the NDVI$_M$ surfaces (Figure 1e), and 74.66% for the NDVI$_D$ surfaces (Figure 1f) which were increased by 7.54%, 18.48% and 17.64%, respectively, compared to the DTB$_{C6}$. The percentage of retrievals within the EE increased from 51% to 57%, 63% to 66%, and 51% to 58%, respectively, compared to the DTB$_{C6}$. The RMSE decreased from 0.232 to 0.194, 0.198 to 0.197, and 0.200 to 0.176, and the RMB decreased from 0.17 to −0.01, 0.11 to 0.09, and 0.28 to 0.22 for NDVI$_P$, NDVI$_M$ and NDVI$_D$ surfaces, respectively. The DTB$_{C6.1}$ AOD retrievals performed better over NDVI$_P$ surfaces in terms of RMB, NDVI$_M$ surfaces in terms of greater numbers of collocations, and NDVI$_D$ surfaces in terms of greater percentage within the EE compared to the DTB$_{C6}$. However, still more improvements in the DTB$_{C6.1}$ and DB$_{C6.1}$ are required for all these surfaces.

For DTB$_{SMS}$, results show significant improvements in spatiotemporal coverage as the fractions of observations coincident with AERONET measurements were 96.25% for the NDVI$_P$ surfaces (Figure 1d), 74.31% for the NDVI$_M$ surfaces (Figure 1e), and 78.37% for the NDVI$_D$ surfaces (Figure 1f) which were increased by 4.67% (16.21%), 3.70% (22.18%), and 3.71% (17.64%), respectively, compared to the DTB$_{C6.1}$ (DTB$_{C6}$). The quality of the DTB$_{SMS}$ AOD retrievals was improved as the percentage of retrievals within the EE increased by 7–12% (20–27%), RMSE decreased by 4–6% (18–54%), and RMB decreased by 4–18% (36–54%). Improvements were observed in DTB$_{SMS}$ in terms of large percentage of retrievals within the EE, a number of collocations and RMB were observed for NDVI$_P$ surfaces compared to the DTB$_{C6}$ and DTB$_{C6.1}$ AOD retrievals. Overall, the performance of the DTB$_{SMS}$ product was better than the DTB$_{C6}$ and DTB$_{C6.1}$ products over Asian sites located over diverse vegetated surfaces.

**Figure 1.** Validation of the DTB$_{C6}$ (a–c), DTB$_{C6.1}$ (d–f) and DTB$_{SMS}$ (g–i) AOD retrievals against AERONET V2 L2 AOD measurements for Asian sites located over NDVI$_P$, NDVI$_M$, and NDVI$_D$ surfaces. Where dashed lines represent the EE envelope and the solid line represents the 1:1 line.
4.1.2. Validation of AOD Retrievals over Diverse Vegetated Surfaces of Africa

Total 241, 2929, and 749 AERONET AOD measurements were available for NDVIP, NDVI\textsubscript{M}, and NDVI\textsubscript{D} surfaces, respectively, and these were available from February to August for NDVIP surfaces, and January to December for NDVI\textsubscript{M} and NDVI\textsubscript{D} surfaces. Like the Asian sites, large numbers of coincident observations were observed for the NDVI\textsubscript{M} surfaces (Figure 2b), but dissimilarly, the numbers of coincident observations of DTB\textsubscript{C6.1} for the NDVIP surfaces (Figure 2a) were lower than the NDVI\textsubscript{D} surfaces (Figure 2c). This indicates that most of the African sites were located over vegetated surfaces (NDVI > 0.3) and this might be a reason for having large numbers of measurements for NDVI > 0.3. The DTB\textsubscript{C6.1} (DTB\textsubscript{C6}) AOD retrievals were available from 64% (56%) to 67% (60%) of the AERONET measurements, and the percentage of the retrievals within the EE and correlation were increased, and the RMSE and RMB were decreased from bright to dark surfaces. Figure 2g–i shows that the correlation coefficient, RMSE, RMB, and the percentage of retrievals within the EE of the DTB\textsubscript{SMS} were within 5% of the DTB\textsubscript{C6} and DTB\textsubscript{C6.1}, whereas, the numbers of collocations were increased by 14–24% compared to the DTB\textsubscript{C6}. Overall, no significant improvements were observed in DTB\textsubscript{C6.1} and DTB\textsubscript{SMS} AOD retrievals compared to the DTB\textsubscript{C6} in terms of the agreement with the AERONET measurements, RMSE, RMB, and the percentage of retrievals within the EE.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Same as Figure 1, but for African sites.

4.1.3. Validation of AOD Retrievals over Diverse Vegetated Surfaces of Europe

Most of the European AERONET sites used in this study were located over moderate to densely vegetated surfaces and large numbers of AOD measurements were available over these sites (NDVI\textsubscript{M} = 9309 and NDVI\textsubscript{D} = 8533), compared to the sites located over NDVIP surfaces (N = 3347). The AOD measurements followed the same pattern as the African sites, i.e., the large numbers of measurements were available for NDVI\textsubscript{M} surfaces followed by NDVI\textsubscript{D} and NDVIP surfaces, but
overall, these measurements were much more in numbers than those were available for Asian and African sites. Figure 3 shows that the performance of the DTBC6 AOD retrievals was better for NDVI_M surfaces as the percentage of retrievals within the EE was 70 which meets the requirements of the EE (Figure 3b), compared to the retrievals for NDVI_P and NDVI_D surfaces. For NDVI_P to NDVI_D surfaces, 28% to 36% of the retrievals were above the EE which led to 24% to 38% an average overestimation in the DTBC6 AOD retrievals, and maximum overestimation was observed for the NDVI_D surfaces, and similar results were also observed for Asian sites. Figure 3d–f shows improvements in the DTBC6.1 AOD retrievals compared to the DTBC6 as the percentage of retrievals within the EE increased from 59% to 70%, 70% to 80%, and 62% to 71%, the number of collocations increased from 1885 to 2070, 5952 to 7007, and 5297 to 6278, and RMSE (RMB) decreased from 0.109 (0.24) to 0.086 (0.18), 0.089 (0.31) to 0.075 (0.18), and 0.097 (0.38) to 0.085 (0.27) for NDVI_P, NDVI_M and NDVI_D surfaces, respectively. These results indicate significant improvements in the DTBC6.1 over European sites due to revised surface reflectance ratios in the DT_C6.1 algorithm. The DTBSMS method significantly improves the results in terms of the number of collocations, the large percentage within the EE, and small RMSE and RMB. The number of collocations increased by 42% (56%), 25% (48%), and 22% (45%), the percentage within the EE increased by 10% (31%), 4% (19%), and 10% (26%), the RMSE decreased by 6% (26%), 8% (22%), and 8% (20%), and the RMB decreased by 67% (75%), 56% (74%), and 44% (61%) for NDVI_P, NDVI_M, and NDVI_D surfaces, respectively, compared to the DTBC6.1 (DTBC6) AOD product. Overall, the DTBSMS method was robust and performed well over European sites for all types of surfaces used in this study (Table 2), compared to the DTBC6 and DTBC6.1 products.

Figure 3. Same as Figure 1, but for European sites.

4.1.4. Validation of AOD Retrievals over Diverse Vegetated Surfaces of North America

The DTBC6 (Figure 4a) and DTBC6.1 (Figure 4d) AOD retrievals for NDVI_P surfaces meet the requirements of the EE as 73% and 75% of the retrievals were within the EE, respectively, whereas the
percentage of retrievals within the EE for NDVIM and NDVID surfaces was much lower. It is worth mentioning that the DTBC6 and DTBC6.1 AOD retrievals have significantly larger error (RMB = 0.77 and 0.61) for NDVIM surfaces (Figure 4b, e), compared to the NDVIP (Figure 4a, d) and NDVID (Figure 4c, f) surfaces. Significant overestimation and underestimation were observed in DTBC6.1 AOD retrievals compared to the DTBC6. The performance of the DTBSMS was same as the DTBC6 in terms of correlation, whereas the number of collocations increased by 10–22% (131–179%), the percentage of retrievals within the EE increased by 3–15% (7–29%), and RMB decreased by 8–28% (28–80%) for the DTBSMS, compared to the DTBC6.1 (DTB6). Overall, low performance was observed for all the methods compared to the other regions which indicate the low performance of the DT and DB algorithms.

4.1.5. Validation of AOD Retrievals over Diverse Vegetated Surfaces of South America

Figure 5 shows that AOD level for NDVIP surfaces (Figure 5a, d, g) was much lower than those observed for NDVIM (Figure 5b, e, h) and NDVID (Figure 5c, f, i) surfaces. Although the percentage of retrievals within the EE for the DTBC6 (Figure 5a), DTBC6.1 (Figure 5d) and DTBSMS (Figure 5g) was higher for NDVIP surfaces than the NDVIM surfaces, but overall, the performance of these methods was lower for NDVIP surfaces as they have large RMB and low correlation. Like other regions, the performance of the DTBSMS was better than the DTBC6 and DTBC6.1 as the percentage of retrievals within the EE and number of collocations were increased, and RMB was decreased. The DTBSMS has a large number of collocations and small RMB for all the surfaces, and greater percentage within the EE for NDVIM and NDVID surfaces compared to the DTBC6 and DTBC6.1. Overall, the performance of the DTBSMS was better than the DTBC6 and DTBC6.1 for all the surfaces except for NDVIP, where it is comparable with the DTBC6.1.
4.2. Validation of DTB\textsubscript{C6}, DTB\textsubscript{C6.1}, and DTB\textsubscript{SMS} AOD over Diverse Vegetated Surfaces at Global Scale

At the global scale, validation of the DTB\textsubscript{C6}, DTB\textsubscript{C6.1}, and DTB\textsubscript{SMS} was conducted over 68 AEROENT sites located at diverse vegetated surfaces (Figure 6). The large numbers of AOD measurements from AERONET were available for NDVI\textsubscript{M} surfaces (N = 27,476) followed by NDVI\textsubscript{D} surfaces (N = 19,286) and NDVI\textsubscript{P} surfaces (N = 15,135). These AOD measurements were available from January to December for all surface types. Fractions of the DTB\textsubscript{C6} AOD retrievals coincident with AERONET AOD measurements were 45%, 47% and 48% for NDVI\textsubscript{P} (Figure 6a), NDVI\textsubscript{M} (Figure 6b), and NDVI\textsubscript{D} (Figure 6c) surfaces, respectively. The correlation coefficient of the DTB\textsubscript{C6} retrievals with the AERONET measurements was $\geq 0.80$ for all the surfaces, 60–63% of the retrievals were within the EE, and 30–33% of the retrievals fell above the EE. The positive value of RMB indicates 21–30% average overestimation in the DTB\textsubscript{C6} AOD retrievals. These results suggest that the combination of estimated surface reflectance and aerosol models used in the DT\textsubscript{C6} and DB\textsubscript{C6} algorithm might have large errors, and overall, the performance of the DTB\textsubscript{C6} was poor over diverse vegetated surfaces at a global scale.

For the DTB\textsubscript{C6.1}, fractions of observations coincident with AERONET AOD measurements were 65% for the NDVI\textsubscript{P} surfaces (Figure 6d), 65% for the NDVI\textsubscript{M} surfaces (Figure 6e), and 66% of the NDVI\textsubscript{D} surfaces (Figure 6f) which were increased by 20%, 18%, and 18%, respectively, compared to the DTB\textsubscript{C6}. The percentage of retrievals within the EE increased from 60% to 69%, 63% to 68%, and 61% to 66%, the RMSE decreased from 0.168 to 0.128, 0.157 to 0.148, and 0.133 to 0.128, and the RMB decreased from 0.22 to 0.05, 0.21 to 0.15, and 0.30 to 0.23 for NDVI\textsubscript{P}, NDVI\textsubscript{M} and NDVI\textsubscript{D} surfaces, respectively. The DTB\textsubscript{C6.1} AOD retrievals meet the requirements of the EE only for NDVI\textsubscript{P} and NDVI\textsubscript{M} surfaces as 69% and 68% of the retrievals were within the EE, respectively, whereas 66% of the retrievals were above the EE for the NDVI\textsubscript{D} surfaces.
For the DTBSMS, results show significant improvements in spatiotemporal coverage at global scale as the fraction of observations of the DTBSMS coincident with AERONET were 76% for the NDVI_P surfaces (Figure 6d), 78% for the NDVI_M surfaces (Figure 6e), and 79% for the NDVI_D surfaces (Figure 6f) which were increased by 11% (31%), 13% (31%), and 13% (31%), respectively, compared to the DTB_C6.1 (DTB_C6). The quality of the DTBSMS AOD retrievals much improved as the percentage of retrievals within the EE increased by 6–9% (14–22%), and RMB decreased by 30–100% (46–100%). Overall, the performance of the DTBSMS product was better than the DTB_C6 and DTB_C6.1 AOD retrievals for NDVI_P, NDVI_M, and NDVI_D surfaces at a global scale. These results suggest that the DB algorithm can retrieve accurate AOD over vegetated surfaces (NDVI > 0.3), and similar results were also observed in our previous study [9]. Therefore it is recommended to consider the DB AOD retrievals for NDVI > 0.3 in the operational merged DTB aerosol product.

![Figure 6. Same as Figure 1, but for 68 global sites.](image)

For statistical significance, an equal number of AOD retrievals for the same geolocations (time and site) were selected from the DTB_C6, DTB_C6.1, and DTBSMS for all the surfaces and validated against the same AERONET AOD measurements at the global scale (Figure 7). The percentage of the DTB_C6 AOD retrievals within the EE was <68%, whereas, the AOD retrievals in the DTB_C6.1 significantly improved as 68–70% of the retrievals were within the EE. Significant improvements were observed for the DTBSMS in terms of large percentage within the EE, and small RMSE and RMB compared to the DTB_C6 and DTB_C6.1. The correlation coefficient for all the methods was same on a global scale. These results suggest that the DTBSMS is robust and better than the DTB_C6 and DTB_C6.1 for NDVI_P, NDVI_M, and NDVI_D surfaces at a global scale and can be used operationally for generation of the merged DTB aerosol product.
5. Discussion

In general, under- and over-estimation in satellite AOD retrievals during clear sky or in the presence of thin aerosol layer are mainly due to over- and under-estimation in the estimated surface reflectance used for aerosol inversion which has more contributions in the TOA reflectance compared to atmospheric path reflectance. Similarly, under- and over-estimation in satellite AOD retrievals in the presence of heavy or thick aerosol layer are mainly due to errors in the aerosol models used in the creation of look-up-table (LUT) for aerosol inversion as the atmospheric path reflectance has more contributions in the TOA reflectance compared to the surface reflectance. These general rules are applicable to all of the available satellites aerosol products, irrespective of their available old and new collections or versions, and such findings have been reported in previous studies [19–22]. Good agreement or high correlation between satellite AOD retrievals and AERONET AOD measurements indicate that the satellite AOD observations follow the same variations in aerosol concentrations as measured by AERONET. However, low correlation and a large percentage of the retrievals within the EE indicate that the satellite AOD observation does not follow the same variations in aerosol concentrations as measured by AERONET but these observations have a small difference and comparable results with AERONET measurements in values [8,9,11].

This study has compared the MOD04 C6 and C6.1 merged aerosol products (DTB_{C6} and DTB_{C6.1}) over the diverse vegetated surfaces using AERONET AOD measurements obtained from 68 global sites from 2004–2014. Additionally, the DTB_{SMS} AOD retrievals were also included for comparison purposes, and these retrievals are different from the DTB_{C6/C6.1} AOD retrievals as the selection of DT
and DB AOD retrievals for DTBC6/C6.1 depends on NDVI \[2,8\], whereas DTBSMS is independent of NDVI and includes all the available highest quality assurance DT and DB retrievals \[9\].

This section mainly discusses the impact of the modifications and improvements on the DTBC6.1 AOD retrievals which have been made for C6.1 compared to the C6. For DT_C6.1, the major modification is the revised and improved ratios for the surface reflectance for the urban areas defined by MOD09 surface reflectance product \[10\]. For DB_C6.1, the main modifications are (i) removal of artifacts from the heterogeneous terrain, (ii) improved surface modeling for elevated terrain, (iii) updated seasonal/regional aerosol models, and (iv) improved internal smoke detection masks.

Comparison for the Asian sites located over NDVI_P, NDVI_M and NDVI_D surfaces shows that the DTBC6 has more AOD retrievals over NDVI_P surfaces compared to the NDVI_M and NDVI_D surface due to greater contribution by the DB AOD retrievals as it performs better and suitable to retrieve more observations than the DT over partially vegetated surfaces \[5,8,11,23\]. The high correlation coefficient for the DTBC6/C6.1 and DTBSMS AOD retrievals with the AERONET measurements for all the surfaces (Figure 1) indicate that these AOD retrievals follow the variations in aerosol concentrations over the Asian sites. Similarly, large percentage of DTBC6/C6.1 and DTBSMS AOD retrievals within the EE for NDVI_M surfaces (Figure 1b,e,h) indicates that the DT AOD retrievals have small differences with the AERONET measurements for 0.3 < NDVI \(\leq 0.5\). Significant overestimation in DTBC6/C6.1 AOD retrievals for the NDVI_D surfaces in the presence of low and high aerosol loadings might be caused by the errors in the estimated surface reflectance and aerosol modes used for aerosol inversion in the DT algorithm \[20–27\]. Although the new surface reflectance scheme \[10\] used in the DT_C6.1 reduced the overestimation as the percentage of retrievals above the EE were decreased from 30–48% to 20–40%, but it does not show significant improvements for all the surfaces, and more improvements are still required. The modifications and improvements in the DB_C6.1 algorithm increased the number of collocations, percentage within the EE and reduced the RMSE and RMB in the DTBSMS compared to the C6.1 as the SMS considers both DT_C6.1 and DB_C6.1 for all the NDVI values \[9\], whereas the DTBC6.1 considers DB only for NDVI < 0.2 \[2,8\]. It is worth mentioning that the modifications in the DB_C6.1 algorithm also led to the underestimation in the AOD retrievals as can be seen in Figure 1g,h.

It is worth mentioning that the DTBC6 and DTBC6.1 underestimate AOD for the NDVI \(\leq 0.5\) surfaces of Africa which might be due to overestimation in the surface reflectance (Figure 2a,b,d,e) \[20–22,24,25\], whereas the estimated surface reflectance seems to be more consistent with the observations for surfaces with NDVI > 0.5 and the DT algorithm performed well over such types of surfaces as has also been reported by others \[28,29\]. The surface reflectance used in DT_C6.1 might have more errors compared to the surface reflectance used in DT_C6 as evident from Figure 2b (RMB = −0.08) and 2e (RMB = −0.19) which contain only DT_C6.1 AOD retrievals.

Significant improvements in DTBC6.1 and DTBSMS AOD retrievals for European sites are mainly due to the improvements in the DT_C6.1 and DB_C6.1 algorithms which led to large numbers of collocations, the greater percentage within the EE and small RMSE and RMB compared to the DTBC6 retrievals. The large error in AOD retrievals for NDVI_D surfaces might be due to the errors in the estimated surface reflectance used in the DT_C6.1 algorithms (Figure 3c,f,i) \[20–22,24,25\]. The improvements in DB_C6.1 played a significant role in the DTBSMS retrievals as shown in Figure 3g,h,i which make it superior to the DTBC6.1. For NDVI_P surfaces, improvements in the DT_C6.1 algorithm increased the percentage of DTBSMS retrievals within the EE, increased the number collocations, and decreased the RMB and RMSE, as these DT_C6.1 retrievals were ignored by DTBC6.1 which were possibly available for NDVI < 0.2 and DTBC6.1 consider only DB retrievals for these surfaces \[2,8\].

The improvements in the DT_C6.1 and DB_C6.1 reduced the error only for the NDVI_P surfaces of North America, whereas the new surface reflectance used in the DT_C6.1 has not shown significant improvements in terms of high correlation, the large percentage within the EE, and small RMB and RMSE for the NDVI_M and NDVI_D surfaces. Overall, the DT_C6.1 AOD retrievals used in DTBC6.1 performed poorly over North American sites might be due to significant errors in the estimated surface reflectance and aerosol model used in LUT. Whereas, the greater contributions of the modified DBC6.1
AOD retrievals used in the DTB$_{\text{SMS}}$ for NDVI$_M$ and NDVI$_D$ surfaces improved the retrieval quality, increased the number of collocations and reduced the errors.

In the presence of high aerosol loadings over South American sites, the DTB$_{\text{C6}}$, DTB$_{\text{C6.1}}$, and DTB$_{\text{SMS}}$ AOD retrievals were under- and over-estimated for NDVI$_M$ surfaces (Figure 5b,e,h) compared to the NDVI$_D$ surfaces (Figure 5c,f,i), and the same pattern of significant underestimation was observed in DTB$_{\text{C6}}$, DTB$_{\text{C6.1}}$, and DTB$_{\text{C6.1}}$ AOD for NDVI$_D$ surfaces. This might be due to the errors in the aerosol models used in LUT for the DT$_{\text{C6/C6.1}}$ algorithms. For low aerosol loadings, under- and over-estimation for NDVI$_P$, NDVI$_M$ and NDVI$_D$ surfaces might be caused by under- and under-estimation in the estimated surface reflectance used in the DB$_{\text{C6/C6.1}}$ and DT$_{\text{C6/C6.1}}$ algorithms, respectively. So, true aerosol properties are important to retrieve accurate high AOD and true surface properties are important to retrieve accurate low AOD.

At the global scale, the high correlation coefficient of the DTB$_{\text{C6/C6.1}}$ and DTB$_{\text{SMS}}$ AOD retrievals with the AERONET measurements for all surfaces indicate that the DTB$_{\text{C6/C6.1}}$ and DTB$_{\text{SMS}}$ follow the trend of actual variations in aerosol concentrations. Significant improvements in the DTB$_{\text{C6.1}}$ AOD retrievals compared to the DTB$_{\text{C6}}$ is due to the new surface reflectance scheme used in the DT$_{\text{C6.1}}$ and improvements in the DB$_{\text{C6.1}}$ algorithm reduced the overestimation in the DTB$_{\text{C6.1}}$ AOD retrievals for the NDVIP surfaces as the percentage of retrievals above the EE decreased from 30% to 19%. Overall, significant improvements in the DTB$_{\text{SMS}}$, specifically for NDVI $> 0.30$, was due to the great contributions of the DB$_{\text{C6.1}}$ AOD retrievals, which were ignored by the DTB$_{\text{C6}}$ and DTB$_{\text{C6.1}}$ products [2,8]. For an equal number of collocations for the same time and sites, the DTB$_{\text{SMS}}$ has better performance in terms of a large number of collocations, the greater percentage within the EE, small RMSE, and RMB as it considered all those available AOD retrievals either from DT$_{\text{C6.1}}$ or DB$_{\text{C6.1}}$ which were possibly ignored by DTB$_{\text{C6.1}}$ due to NDVI threshold criteria.

6. Summary and Conclusions

In this study, the DTB$_{\text{C6}}$, DTB$_{\text{C6.1}}$, and DTB$_{\text{SMS}}$ AOD retrievals were validated at global scale from 2004–2014 against AERONET Version 2 Level 2.0 AOD measurements obtained from 68 sites located over diverse vegetated surfaces, i.e., partially/non–vegetated (NDVI$_P \leq 0.3$), moderately–vegetated (0.3 < NDVI$_M$ ≤ 0.5) and densely–vegetated (NDVI$_D$ > 0.5) surfaces, categorized by static values of monthly NDVI observations obtained from the MOD13A3 C6 L3 product. The DTB$_{\text{C6}}$ and DTB$_{\text{C6.1}}$ AOD products are accomplished by the NDVI criteria [2]: (i) use the DT AOD retrievals for NDVI $> 0.3$, (ii) use the DB AOD retrievals for NDVI $< 0.2$, and (iii) use an average of the DT and DB AOD retrievals or the available one with highest quality assurance flag (DT: QAF = 3; DB: QAF ≥ 2) for 0.2 $\leq$ NDVI $\leq 0.3$. The DTB$_{\text{SMS}}$ product was accomplished using Simplified Merge Scheme (SMS) [9,17], i.e. use an average of the DT$_{\text{C6.1}}$ and DB$_{\text{C6.1}}$ highest quality assurance AOD retrievals or the available one for all values of NDVI. For this, only those DT and DB AOD retrievals at 550 nm passing recommended quality assurance checks were used (for DT, corresponding to retrievals flagged QAF = 3; for DB, retrievals flagged QAF ≥ 2). Results showed that the number of coincident observations and the percentage of retrievals within/above/below the EE, and RMB were significantly improved for the DTB$_{\text{SMS}}$ at the regional to global scales, compared to the DTB$_{\text{C6}}$ and DTB$_{\text{C6.1}}$. The main outcomes of this study are:

(i) The DTB$_{\text{C6}}$ and DTB$_{\text{C6.1}}$ AOD retrievals performed well for the sites located over NDVI$_M$ surfaces in Asia, whereas, large errors were observed for NDVI$_D$ surfaces might be due to errors in the estimated surface reflectance and aerosol models used for the DT$_{\text{C6}}$ and DT$_{\text{C6.1}}$ algorithm, as the DTB$_{\text{C6}}$ and DTB$_{\text{C6.1}}$ only have DT AOD retrievals for NDVI$_D$ surfaces. This suggests that the new ratios for surface reflectance estimation in the DT$_{\text{C6.1}}$ do not significantly improve the AOD retrievals over NDVI$_D$ surfaces of Asia, and more improvements are required.

(ii) All the AOD retrievals performed well in terms of correlation and large percentage within the EE, but significant underestimation was observed for the DTB$_{\text{C6.1}}$ and DTB$_{\text{SMS}}$ AOD retrievals.
over NDVIp and NDVIm surfaces of Africa which might be due to overestimation in the newly estimated surface reflectance used in the DTc6.1 algorithm.

(iii) For European sites, the DTbcs AOD retrievals performed well for the sites located over NDVIm surfaces compared to the NDVIp and NDVIP surfaces in terms of a large number of observations, the large percentage within the EE, and small RMSE. Whereas, the performance of the DTbc6.1 AOD retrievals was better than the DTbc6 due to improved surface reflectance scheme used in the DTc6.1.

(iv) The DTbc6 and DTbc6.1 AOD retrievals have a large error for the sites located over NDVIm surfaces of North America during low to high aerosol loadings which suggests that significant improvements are required in the surface reflectance method and aerosol models used in the DT algorithm.

(v) For South American sites, significant improvements are required in DTc6.1 AOD retrievals, especially for NDVIm surfaces as less than 60% of the retrievals, were within the EE.

(vi) The DTbSMS is robust and performed better than the DTbc6 and DTbc6.1 for all types of land surfaces used in this study, and significantly improved the number of observations, the percentage of retrievals within the EE, and RMB at the regional scale.

(vii) At the global scale, the DTbc6 has low retrieval quality as AOD retrievals do not meet the requirements of the EE (<68%) for diverse vegetated surfaces, whereas the DTc6.1 has better performance for the NDVIp and NDVImp surfaces, but still improvements are required for NDVIP surfaces. The DTbSMS AOD retrievals meet the requirements of the EE (72–73%) with more available collocations, and small RMSE and RMB, compared to the DTbc6 and DTbc6.1.

These results suggest that the DB AOD retrievals should be considered over moderate and dense vegetated surfaces (NDVI > 0.3) in the operational merged DTB AOD product because sometimes, the DT algorithm does not perform well over these surfaces, and the inclusion of DB can improve the retrievals quality and reduce the errors in the merged product.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Abbreviations

The following abbreviations are used in this manuscript:

- AERONET: Aerosol Robotic Network
- AOD: Aerosol Optical Depth
- C6: Collection 6
- DAAC: Distributed Active Archive Center
- DB: Deep Blue
- DT: Dark Target
- DTB: Dark Target and Deep Blue combined aerosol product
- EE: Expected Error
- LAADS: Level-1 and Atmosphere Archive & Distribution System
- LUT: Look Up Table
- L1: Level-1
- L2: Level-2
- L3: Level-3
MODIS Moderate Resolution Imaging Spectroradiometer
MODIS13A3 MODIS C6 monthly level-3 Normalized Difference Vegetation Index product
MOD04 MODIS level-2 operational aerosol product for Terra
MYD04 MODIS level-2 operational aerosol product for Aqua
N Number of collocations
NDVI Normalized Difference Vegetation Index
NDVI_D NDVI over densely–vegetated surfaces
NDVI_M NDVI over moderately–vegetated surfaces
NDVI_P NDVI over partially/non–vegetated surfaces
QAF Quality Assurance Flag
RMB Relative Mean Bias
SDS Scientific Data Set
SMS Simplified Merge Scheme
TOA Top of Atmosphere reflectance
V2 Version 2
α440–675 Ångström exponent 440–675 nm

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