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

Muhammad Bilal [1], Majid Nazeer [2], Zhongfeng Qiu [1,*], Xiaoli Ding [3] and Jing Wei [4]

1 School of Marine Sciences, Nanjing University of Information Science & Technology, Nanjing 210044, China; muhammad.bilal@connect.polyu.hk
2 Earth and Atmospheric Remote Sensing Lab. (EARL), Department of Meteorology, COMSATS Institute of Information Technology, Islamabad 45550, Pakistan; majid.nazeer@comsats.edu.pk
3 Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hung Hom, Kowloon 999077, Hong Kong, China; xl.ding@polyu.edu.hk
4 College of Geomatics, Shandong University of Science and Technology, Qingdao 266590, China; weijing_rs@163.com
* Correspondence: zhongfeng.qiu@nuist.edu.cn; Tel.: +86-132-5181-2371

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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 ($NDVI_P \leq 0.3$), moderately–vegetated ($0.3 < NDVI_M \leq 0.5$) 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 $\geq$ 2) for $0.2 \leq NDVI \leq 0.3$. 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 ($EE = \pm (0.05 + 0.15 \times AOD)$). 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 µm. 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 µm 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 $\pm(0.05 + 0.15 \times AOD_{AERONET})$) [2]. The EE represents a one standard deviation confidence interval around the retrieved AOD, i.e., about 68% of points should fall within ±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 µm 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 µm 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 $\geq$ 2) for 0.2 $\leq$ NDVI $\leq$ 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 ($NDVI_P \leq 0.3$), moderately–vegetated surfaces ($0.3 < NDVI_M \leq 0.5$) 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 $\geq$ 2 over land
	AOD_550_Dark_Target_Deep_Blue_Combined	AOD of QAF = 1 to 3 over land and ocean
	AOD_550_Dark_Target_Deep_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	28.2800
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	39.977	116.381	NhaTran	12.205	109.21
Chiang Mai Met Sta.	18.7710	98.9720	Pune	18.5370	73.8050
Jaipur	26.9060	75.8060	Silpakorn Univ	13.8190	100.0410
Kanpur	26.5130	80.2320	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	43.9330	4.878	Minsk	53.920	27.601
Brussels	50.7830	4.350	Moscow MSU MO	55.700	37.510
Cabauw	51.9710	4.9270	Munich University	48.1480	11.5730
Carpentras	44.0830	5.0580	OHP OBSERVATOIRE	43.9350	5.710
Chilbolton	51.1440	−1.4370	Palaiseau	48.700	2.2080
Granada	37.1640	−3.6050	Paris	48.8670	2.3330
Hamburg	53.5680	9.9730	Rome Tor Vergata	41.840	12.647
Ispra	45.8030	8.6270	Toravere	58.2550	26.460
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
Billerica	42.5280	−71.2690	KONZA EDC	39.1020	−96.6100
BONDVILLE	40.0530	−88.3720	Missoula	46.9170	−114.0830
Bozeman	45.6620	−111.0450	Rimrock	46.4870	−116.9920
BSRN_BAO Boulder	40.0450	−105.0060	Sevilleta	34.3550	−106.8850
CalTech	34.1370	−118.1260	Sioux Falls	43.7360	−96.6260
Dayton	39.7760	−84.1100	TABLE MOUNTAIN CA	34.3800	−117.6800
Frenchman Flat	36.8090	−115.9350	Tucson	32.2330	−110.9530
Fresno	36.7820	−119.7730	UCSB	34.4150	−119.8450
Georgia Tech	33.7800	−84.4000	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	−54.5380	Manaus EMBRAPA	−2.8910	−59.9700
CASLEO	−31.7990	−69.3060	Rio Branco	−9.9570	−67.8690
CEILAP-BA	−34.5670	−58.5000	Sao Martinho SONDA	−29.4430	−53.8230

3. Methods

In this study, the DTB_{C6}, $DTB_{C6.1}$, and DTB_{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_{C6} and $DTB_{C6.1}$ 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_{SMS}, the $DT_{C6.1}$ highest quality assurance flag (QAF = 3) AOD retrievals were obtained from the SDS "Optical_Depth_Land_And_Ocean" and the $DB_{C6.1}$ highest quality assurance flag (QAF $\geq$ 2) AOD retrievals were obtained from the SDS "Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate". The DTB_{SMS} product is generated by Simplified Merge Scheme (SMS) [9,17], 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 [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 $DTB_{C6}/DTB_{C6.1}/DTB_{SMS}$ within a spatial region of 3 × 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 DTB_{C6}, $DTB_{C6.1}$, and DTB_{SMS} AOD retrievals were filtered for three diverse types of land surfaces, i.e., partially/non–vegetated ($NDVI_P \leq 0.3$), moderated–vegetated ($0.3 < NDVI_M \leq 0.5$) and dense–vegetated ($NDVI_D > 0.5$) 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 DTB_{C6} AOD retrievals, but in this study, static values of NDVI were used as the DTB_{C6} and $DTB_{C6.1}$ 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)

$$RMB = \left(\frac{\overline{\text{AOD}}_{(\text{MODIS})} - \overline{\text{AOD}}_{(\text{AERONET})}}{\overline{\text{AOD}}_{(\text{AERONET})}} \right) \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\text{AOD}_{(\text{MODIS})i} - \text{AOD}_{(\text{AERONET})i}\right)^2} \quad (2)$$

$$\text{EE} = \pm\left(0.05 + 0.15 \times \text{AOD}_{(\text{AERONET})}\right) \quad (3)$$

$$\%\ \text{Relative Difference} = \left(\frac{\text{DTB}_{\text{C6.1}} - \text{DTB}_{\text{SMS}}}{\text{DTB}_{\text{C6.1}}}\right) \times 100 \quad (4)$$

4. Results

To point out an efficient and robust aerosol product among the DTB_{C6}, $DTB_{C6.1}$, and DTB_{SMS}, 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 DTB_{C6}, $DTB_{C6.1}$, and DTB_{SMS} AOD over Diverse Vegetated Surfaces at Regional Scale

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

Validation of the DTB_{C6}, $DTB_{C6.1}$, and DTB_{SMS} 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 DTB_{C6} product has 31.91% and 27.02% more retrievals over $NDVI_P$ surfaces (2465/2933 × 100 = 84.04%) (Figure 1a) than the $NDVI_M$ (Figure 1b: 52.13%) and $NDVI_D$ (Figure 1c: 57.02%) surfaces, respectively. The DTB_{C6} AOD retrievals have correlation coefficient ≥ 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%, 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 greater percentage within the EE compared to the DTB_{C6}. However, still more improvements in the $DT_{C6.1}$ 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% (18–19%), 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 $NDVI_P$ and $NDVI_D$ 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.

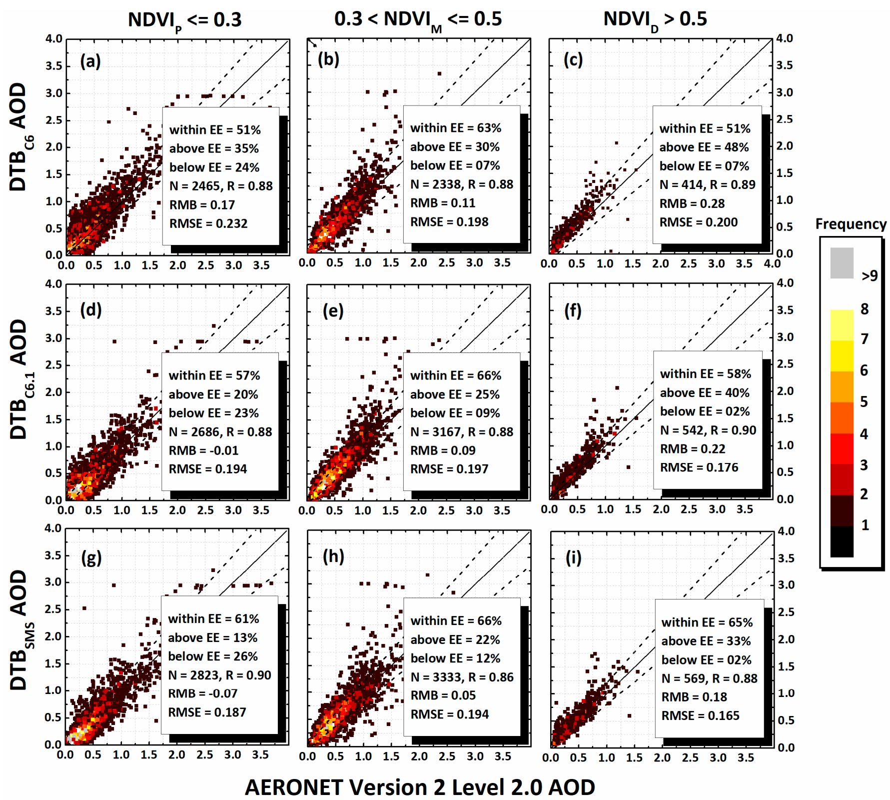

Figure 1. Validation of the DTB_{C6} (**a**–**c**), $DTB_{C6.1}$ (**d**–**f**) and DTB_{SMS} (**g**–**i**) AOD retrievals against AERONET V2 L2 AOD measurements for Asian sites located over $NDVI_P$, $NDVI_M$, and $NDVI_D$ surfaces. Where dashed lines represent the EE envelope and the solid line represents the1:1 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 $NDVI_P$, $NDVI_M$, and $NDVI_D$ surfaces, respectively, and these were available from February to August for $NDVI_P$ surfaces, and January to December for $NDVI_M$ and $NDVI_D$ surfaces. Like the Asian sites, large numbers of coincident observations were observed for the $NDVI_M$ surfaces (Figure 2b), but dissimilarly, the numbers of coincident observations of $DTB_{C6.1}$ for the $NDVI_P$ surfaces (Figure 2a) were lower than the $NDVI_D$ 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 $DTB_{C6.1}$ (DTB_{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_{SMS} were within 5% of the DTB_{C6} and $DTB_{C6.1}$, whereas, the numbers of collocations were increased by 14–24% compared to the DTB_{C6}.Overall, no significant improvements were observed in $DTB_{C6.1}$ and DTB_{SMS} AOD retrievals compared to the DTB_{C6} in terms of the agreement with the AERONET measurements, RMSE, RMB, and the percentage of retrievals within the EE.

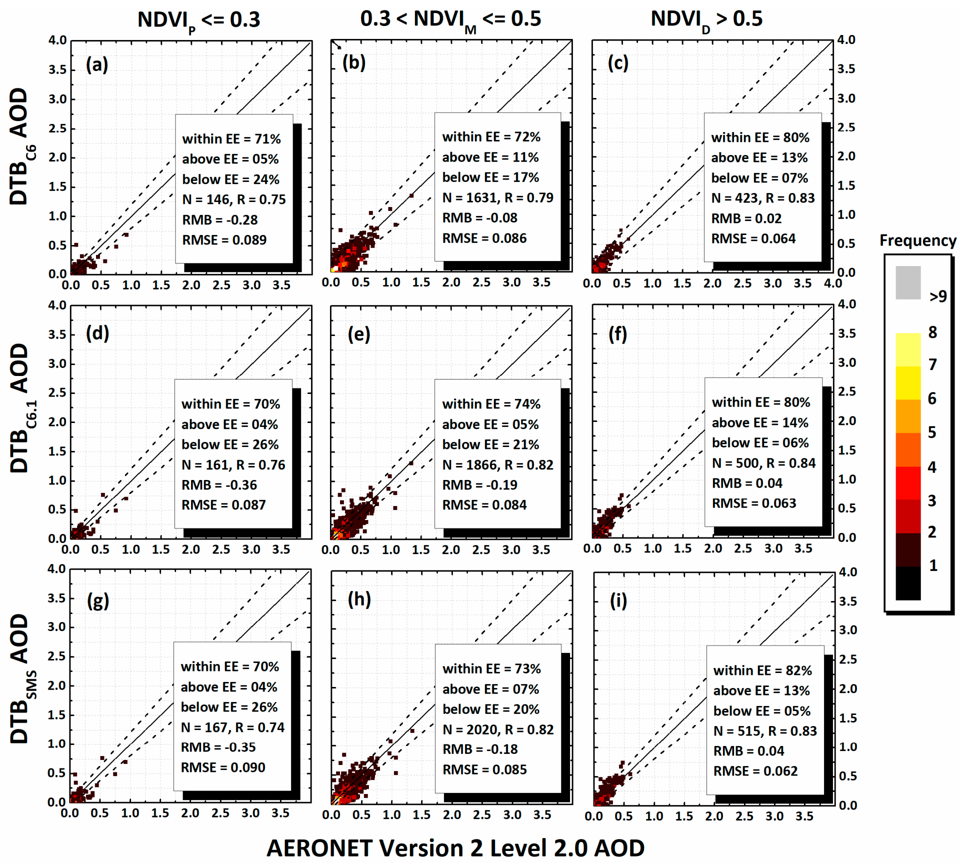

Figure 2. Same as Figure 1, but for African sites.

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

Most of the European AEORNET sites used in this study were located over moderate to densely vegetated surfaces and large numbers of AOD measurements were available over these sites ($NDVI_M$ = 9309 and $NDVI_D$ = 8533), compared to the sites located over $NDVI_P$ surfaces (N = 3347). The AOD measurements followed the same pattern as the African sites, i.e., the large numbers of measurements were available for $NDVI_M$ surfaces followed by $NDVI_D$ and $NDVI_P$ 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 DTB_{C6} 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 $DTB_{C6.1}$ AOD retrievals compared to the DTB_{C6} 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 $DTB_{C6.1}$ over European sites due to revised surface reflectance ratios in the $DT_{C6.1}$ algorithm. The DTB_{SMS} 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 $DTB_{C6.1}$ (DTB_{C6}) AOD product. Overall, the DTB_{SMS} method was robust and performed well over European sites for all types of surfaces used in this study (Table 2), compared to the DTB_{C6} and $DTB_{C6.1}$ products.

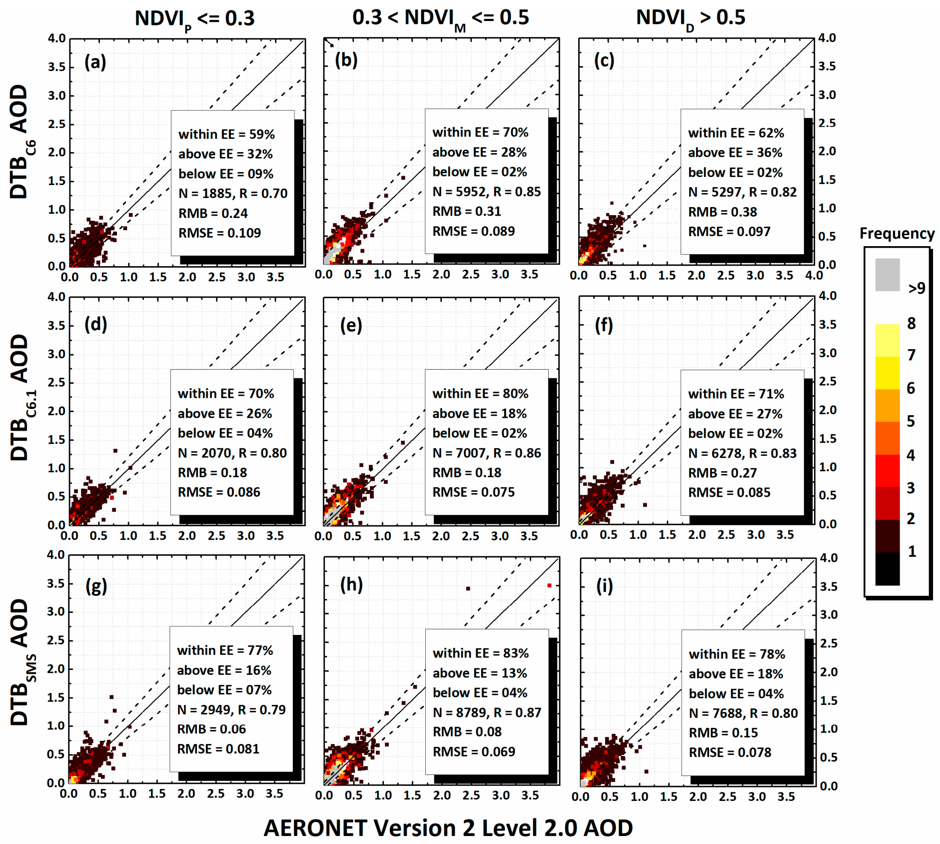

Figure 3. Same as Figure 1, but for European sites.

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

The DTB_{C6} (Figure 4a) and $DTB_{C6.1}$ (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 $NDVI_M$ and $NDVI_D$ surfaces was much lower. It is worth mentioning that the DTB_{C6} and $DTB_{C6.1}$ AOD retrievals have significantly larger error (RMB = 0.77 and 0.61) for $NDVI_M$ surfaces (Figure 4b,e), compared to the $NDVI_P$ (Figure 4a,d) and $NDVI_D$ (Figure 4c,f) surfaces. Significant overestimation and underestimation were observed in $DTB_{C6.1}$ AOD retrievals compared to the $DTB_{C6.}$ The performance of the DTB_{SMS} was same as the DTB_{C6} 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 DTB_{SMS}, compared to the $DTB_{C6.1}$ (DTB_{C6}). 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.

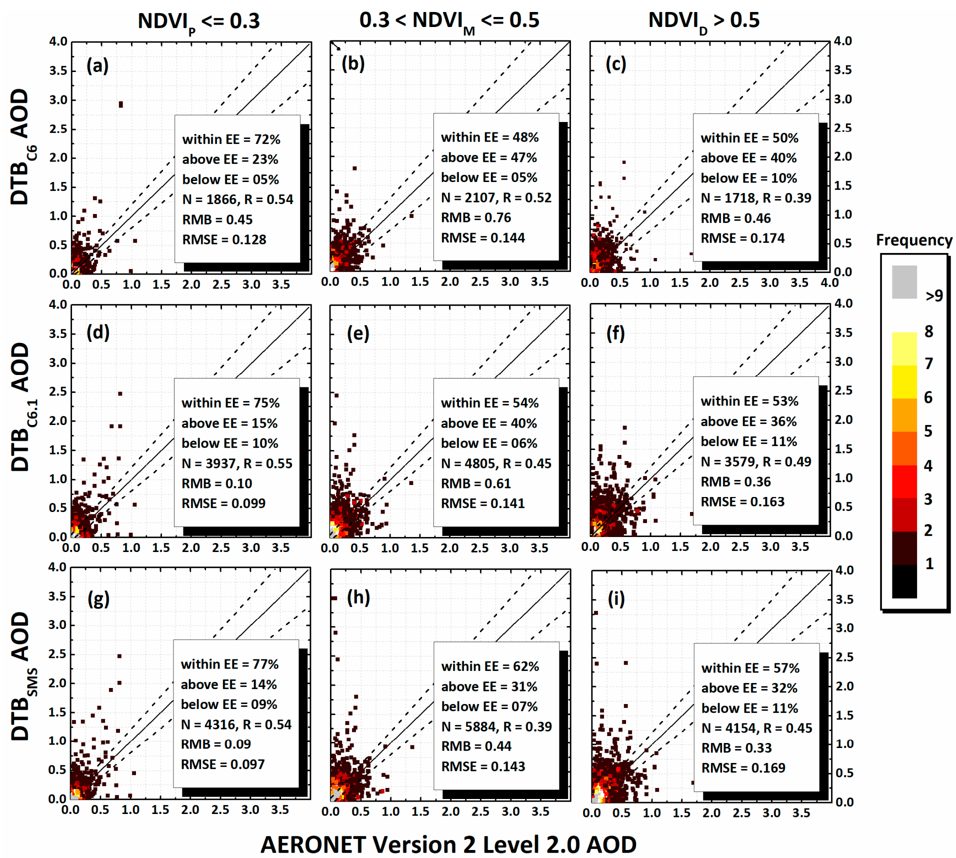

Figure 4. Same as Figure 1, but for North American sites.

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

Figure 5 shows that AOD level for $NDVI_P$ surfaces (Figure 5a,d,g) was much lower than to those observed for $NDVI_M$ (Figure 5b,e,h) and $NDVI_D$ (Figure 5c,f,i) surfaces. Although the percentage of retrievals within the EE for the DTB_{C6} (Figure 5a), $DTB_{C6.1}$ (Figure 5d) and DTB_{SMS} (Figure 5g) was higher for $NDVI_P$ surfaces than the $NDVI_M$ surfaces, but overall, the performance of these methods was lower for $NDVI_P$ surfaces as they have large RMB and low correlation. Like other regions, the performance of the DTB_{SMS} was better than the DTB_{C6} and $DTB_{C6.1}$ as the percentage of retrievals within the EE and number of collocations were increased, and RMB was decreased. The DTB_{SMS} has a large number of collocations and small RMB for all the surfaces, and greater percentage within the EE for $NDVI_M$ and $NDVI_D$ surfaces compared to the DTB_{C6} and $DTB_{C6.1}$. Overall, the performance of the DTB_{SMS} was better than the DTB_{C6} and $DTB_{C6.1}$ for all the surfaces except for $NDVI_P$, where it is comparable with the $DTB_{C6.1}$.

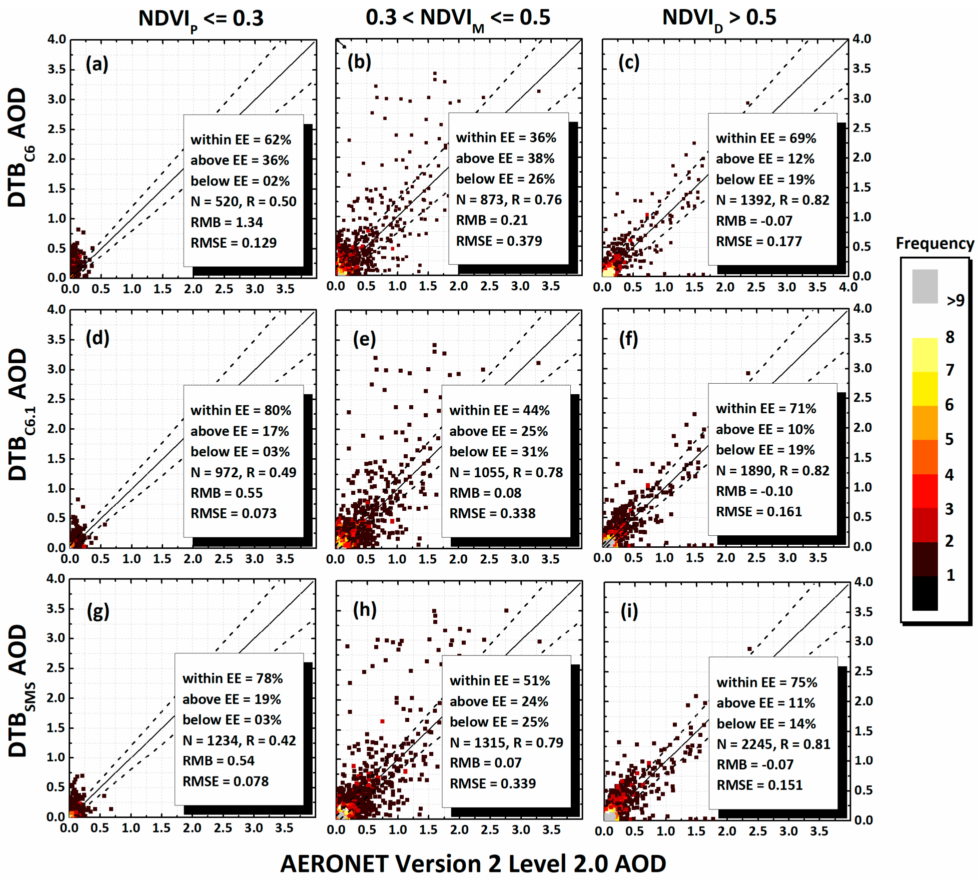

Figure 5. Same as Figure 1, but for South American sites.

4.2. Validation of DTB_{C6}, $DTB_{C6.1}$, and DTB_{SMS} AOD over Diverse Vegetated Surfaces at Global Scale

At the global scale, validation of the DTB_{C6}, $DTB_{C6.1}$, and DTB_{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 $NDVI_M$ surfaces (N = 27,476) followed by $NDVI_D$ surfaces (N = 19,286) and $NDVI_P$ surfaces (N = 15,135). These AOD measurements were available from January to December for all surface types. Fractions of the DTB_{C6} AOD retrievals coincident with AERONET AOD measurements were 45%, 47% and 48% for $NDVI_P$ (Figure 6a), $NDVI_M$ (Figure 6b), and $NDVI_D$ (Figure 6c) surfaces, respectively. The correlation coefficient of the DTB_{C6} retrievals with the AEROENT 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_{C6} AOD retrievals. These results suggest that the combination of estimated surface reflectance and aerosol models used in the DT_{C6} and DB_{C6} algorithm might has large errors, and overall, the performance of the DTB_{C6} was poor over diverse vegetated surfaces at a global scale.

For the $DTB_{C6.1}$, fractions of observations coincident with AERONET AOD measurements were 65% for the $NDVI_P$ surfaces (Figure 6d), 65% for the $NDVI_M$ surfaces (Figure 6e), and 66% of the $NDVI_D$ surfaces (Figure 6f) which were increased by 20%, 18%, and 18%, respectively, compared to the DTB_{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 $NDVI_P$, $NDVI_M$ and $NDVI_D$ surfaces, respectively. The $DTB_{C6.1}$ AOD retrievals meet the requirements of the EE only for $NDVI_P$ and $NDVI_M$ surfaces as 69% and 68% of the retrievals were within the EE, respectively, whereas 66% of the retrievals were above the EE for the $NDVI_D$ surfaces.

For the DTB_{SMS}, results show significant improvements in spatiotemporal coverage at global scale as the fraction of observations of the DTB_{SMS} 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 DTB_{SMS} 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 DTB_{SMS} 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.

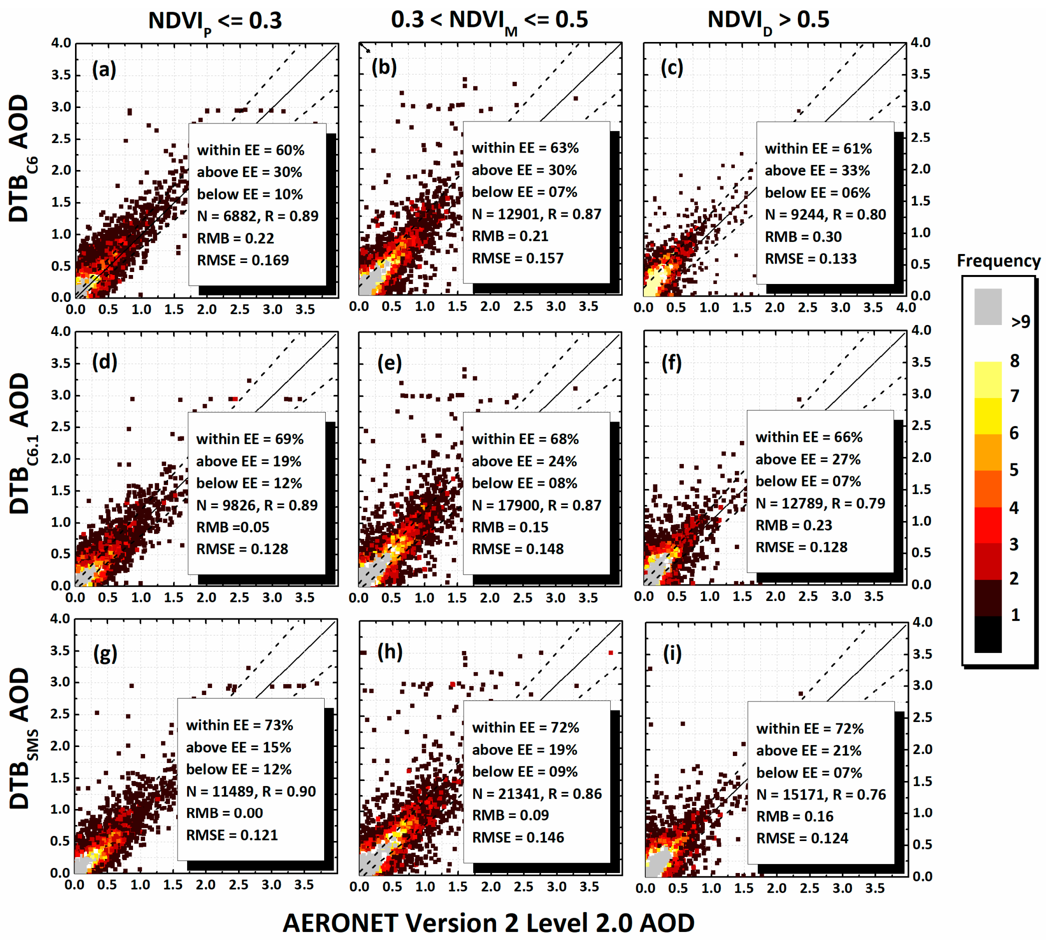

Figure 6. Same as Figure 1, but for 68 global sites.

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 DTB_{SMS} for all the surfaces and validated against the same AEROENT AOD measurements at the global scale (Figure 7). The percentage of the DBT_{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 DTB_{SMS} 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 DTB_{SMS} 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.

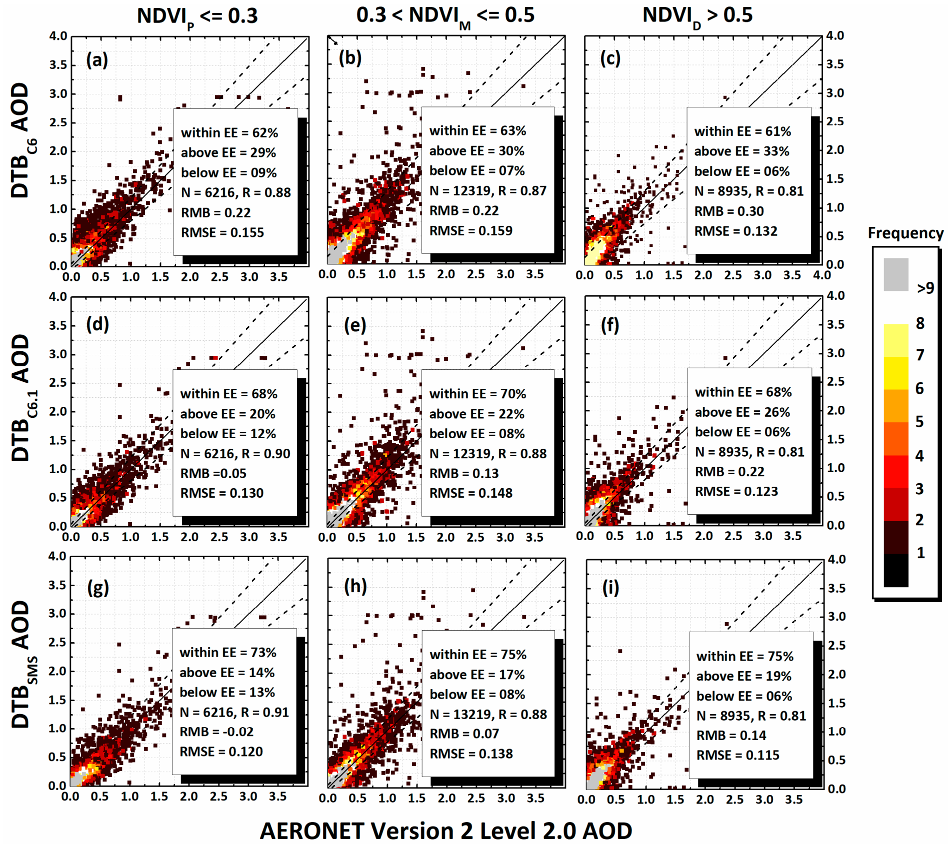

Figure 7. Validation of an equal number of the DTB_{C6} (**a–c**), $DTB_{C6.1}$ (**d–f**) and DTB_{SMS} (**g–i**) AOD retrievals for the same geolocations (time and place) against the same AERONET L2 V2 AOD measurements for 68 global sites located over $NDVI_P$, $NDVI_M$, and $NDVI_D$ surfaces. Where dashed lines represent the EE envelope and the solid line represents the 1:1 line.

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 $DTB_{C6/C6.1}$ depends on NDVI [2,8], whereas DTB_{SMS} 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 $DTB_{C6.1}$ 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 DTB_{C6} 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 $DTB_{C6/C6.1}$ and DTB_{SMS} 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 $DTB_{C6/C6.1}$ and DTB_{SMS} 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 $DTB_{C6/C6.1}$ 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 DTB_{SMS} 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 $DTB_{C6.1}$ 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 DTB_{C6} and $DTB_{C6.1}$ 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 has 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 $DTB_{C6.1}$ and DTB_{SMS} 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 DTB_{C6} 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 $DT_{C6/C6.1}$ algorithms (Figure 3c,f,i) [20–22,24,25]. The improvements in $DB_{C6.1}$ played a significant role in the DTB_{SMS} retrievals as shown in Figure 3g,h,i which make it superior to the $DTB_{C6.1}$. For $NDVI_P$ surfaces, improvements in the $DT_{C6.1}$ algorithm increased the percentage of DTB_{SMS} retrievals within the EE, increased the number collocations, and decreased the RMB and RMSE, as these $DT_{C6.1}$ retrievals were ignored by $DTB_{C6.1}$ which were possibly available for $NDVI < 0.2$ and $DTB_{C6.1}$ 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 $DTB_{C6.1}$ 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_{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_{C6}, $DTB_{C6.1}$, and DTB_{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_{C6}, $DTBC_{6.1,}$ and $DTBC_{6.1}$ AOD for $NDVI_D$ surfaces. This might be due to the errors in the aerosol models used in LUT for the $DT_{C6/C6.1}$ algorithms. For low aerosol loadings, under- and over-estimation for $NDVI_P$ $NDVI_M$ and $NDVI_D$ surfaces might be caused by over- and under-estimation in the estimated surface reflectance used in the $DB_{C6/C6.1}$ and $DT_{C6/C6.1}$ 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 $DTB_{C6/C6.1}$ and DTB_{SMS} AOD retrievals with the AEROENT measurements for all surfaces indicate that the $DTB_{C6/C6.1}$ and DTB_{SMS} **follow the trend** of actual variations in aerosol concentrations. Significant improvements in the $DTB_{C6.1}$ AOD retrievals compared to the DTB_{C6} is due to the new surface reflectance scheme used in the $DT_{C6.1}$ and improvements in the $DB_{C6.1}$ algorithm reduced the overestimation in the $DTB_{C6.1}$ 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_{SMS}, specifically for NDVI > 0.30, was due to the great contributions of the $DB_{C6.1}$ AOD retrievals, which were ignored by the DTB_{C6} and $DTB_{C6.1}$ products [2,8]. For an **equal** number of collocations for the same time and sites, the DTB_{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 $DT_{C6.1}$ or $DB_{C6.1}$ which were possibly ignored by $DTB_{C6.1}$ due to NDVI threshold criteria.

6. Summary and Conclusions

In this study, the DTB_{C6}, $DTB_{C6.1}$, and DTB_{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 ($0.3 < NDVI_M \leq 0.5$) 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_{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 flag (DT: QAF = 3; DB: QAF ≥ 2) for 0.2 ≤ NDVI ≤ 0.3. The DTB_{SMS} product was accomplished using Simplified Merge Scheme (SMS) [9,17], i.e. use an average of the $DT_{C6.1}$ and $DB_{C6.1}$ 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_{SMS} at the regional to global scales, compared to the DTB_{C6} and $DTB_{C6.1}$. The main outcomes of this study are:

(i) The DTB_{C6} and $DTB_{C6.1}$ 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_{C6} and $DT_{C6.1}$ algorithm, as the DTB_{C6} and $DTB_{C6.1}$ only have DT AOD retrievals for $NDVI_D$ surfaces. This suggests that the new ratios for surface reflectance estimation in the $DT_{C6.1}$ 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 $DTB_{C6.1}$ and DTB_{SMS} AOD retrievals over $NDVI_P$ and $NDVI_M$ surfaces of Africa which might be due to overestimation in the newly estimated surface reflectance used in the $DT_{C6.1}$ algorithm.

(iii) For European sites, the DTB_{C6} AOD retrievals performed well for the sites located over $NDVI_M$ surfaces compared to the $NDVI_P$ and $NDVI_D$ surfaces in terms of a large number of observations, the large percentage within the EE, and small RMSE. Whereas, the performance of the $DTB_{C6.1}$ AOD retrievals was better than the DTB_{C6} due to improved surface reflectance scheme used in the $DT_{C6.1}$.

(iv) The DTB_{C6} and $DTB_{C6.1}$ AOD retrievals have a large error for the sites located over $NDVI_M$ 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 $DT_{C6.1}$ AOD retrievals, especially for $NDVI_M$ surfaces as less than 60% of the retrievals, were within the EE.

(vi) The DTB_{SMS} is robust and performed better than the DTB_{C6} and $DTB_{C6.1}$ 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 DTB_{C6} has low retrieval quality as AOD retrievals do not meet the requirements of the EE (<68%) for diverse vegetated surfaces, whereas the $DT_{C6.1}$ has better performance for the $NDVI_P$ and $NDVI_M$ surfaces, but still improvements are required for $NDVI_D$ surfaces. The DTB_{SMS} AOD retrievals meet the requirements of the EE (72–73%) with more available collocations, and small RMSE and RMB, compared to the DTB_{C6} and $DTB_{C6.1}$.

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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Author Contributions: Muhammad Bilal designed and wrote the paper; Majid Nazeer, Zhongfeng Qiu, and Xiaoli Ding reviewed and modified the paper, and Majid Nazeer and Jing Wei helped in data processing.

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
MOD13A3	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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