Atmospheric Environment 202 (2019) 315–327

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Improved merge schemes for MODIS Collection 6.1 Dark Target and Deep Blue combined aerosol products

Jing Wei[a], Zhanqing Li[b,*], Lin Sun[c], Yiran Peng[d], Lunche Wang[e]

[a] State Key Laboratory of Remote Sensing Science, College of Global Change and Earth System Science, Beijing Normal University, Beijing, China
[b] Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
[c] College of Geomatics, Shandong University of Science and Technology, Qingdao, China
[d] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China
[e] Hubei Key Laboratory of Critical Zone Evolution, School of Earth Sciences, China University of Geosciences, Wuhan, China

ARTICLE INFO

Keywords:
MODIS
Collection C6.1
Improved merge schemes
DTB
AERONET

ABSTRACT

Our previous study illustrated that the operational Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6.1 (C6.1) Dark Target (DT) and Deep Blue (DB) combined products (denoted as DTB0) are not always the best in most regions due to its unsuitable merge approach. Therefore, the objective of this study is to develop an improved merge approach to increase the spatiotemporal data coverage and reduce the estimation uncertainty. For this, three tests, i.e., a land-use-type test, a surface-relief test, and an aerosol-type test are performed according to the strengths and weakness of the performances of the DT and DB algorithms with their high-quality assurance retrievals (QA = 3 for DT and QA ≥ 2 for DB) against the newest Aerosol Robotic Network (AERONET) Version 3 Level 2.0 measurements. Based on this, new merged DT and DB products (denoted as DTB1) are generated. The Terra and Aqua DTB1 products are then validated against AERONET measurements at 286 sites on site, continental, and global scales, and for varying underlying surfaces and elevated terrains from 2013 to 2017. The DTB0 products for the same period are collected for comparison. More than 90% of the sites now have more data points, and the performances of the DTB1 products are improved with an increased percentage of the data falling within the expected error [± (0.05 + 15%)] envelope and reduced mean absolute errors and root-mean-square errors compared with DTB0 products at most sites. Separate- and equal-number comparisons show that the DTB1 products significantly improve both the data coverage and data quality. The new merged products are more accurate and less affected by varying surface structures than the operational products. These results suggest that the improved merge approach is more robust and can be used for generating more accurate global aerosol products.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua satellite platforms were launched into sun-synchronous polar orbits in December 1999 and May 2002, respectively. They acquire data at 36 spectral channels ranging from 0.405 to 14.385 μm at three spatial resolutions (250 m, 500 m, and 1 km). They have a viewing swath width of 2330 km and can observe the earth's surface every 1–2 days (Sun et al., 2016a). Two global-coverage aerosol products are generated from MODIS measurements: the Level-2 daily (swath) product at 10-km (MxD04_L2, where x = O for Terra and x = Y for Aqua) and 3-km (MxD04_3K) spatial resolutions, and the Level-3 daily (MxD08_D3), 8-day (MxD08_E3), and monthly (MxD08_M3) products at a $1 \times 1^{\circ}$ resolution. MxD08 products are spatiotemporally aggregated from MxD04_L2 products, which are generated from three well-known algorithms: the Dark Target (DT) algorithm over land and ocean (Kaufman et al., 1997; Levy et al., 2007, 2013; Gupta et al., 2016) and the Deep Blue (DB) algorithm (Hsu et al., 2004, 2006, 2013). Thanks to continuous improvements made to data radiometric calibration and aerosol retrieval algorithms, updated versions of operational aerosol products have been made available over the years, e.g., Collection 4 (C4), C5, and C6 to the latest C6.1 released in July 2017. The C6.1 products are based on the newest updated C6.1 Level 1B calibrated radiance products with additional calibration corrections (Jeong et al., 2011; Meister et al., 2014; Wei et al., 2019).

The latest second-generation operational DT algorithm (Levy et al., 2007, 2013) is used to produce the DT dataset over land and ocean. It is designed for dark-target surfaces where the surface reflectances for

* Corresponding author.
E-mail address: zli@atmos.umd.edu (Z. Li).

https://doi.org/10.1016/j.atmosenv.2019.01.016
Received 12 October 2018; Received in revised form 12 January 2019; Accepted 14 January 2019
Available online 18 January 2019
1352-2310/

visible channels are determined via dynamic empirical relationships between top-of-the-atmosphere reflectances at the shortwave infrared channels related to the shortwave-infrared Normal Difference Vegetation Index (NDVI) and scattering angle. Five aerosol types are assumed using the cluster analysis with Aerosol Robotic Network (AERONET) measurements for each season. For retrieval purposes, the 20% darkest and 50% brightest pixels are discarded in a 20 × 20 box around a site, and the TOA reflectances for the remaining pixels are averaged. If the number of remaining pixels is greater than 50, the retrieval is considered to have the highest quality assurance (QA = 3). The QA flags when there are more than 30, 20, and 12 pixels are QA = 2, 1, and 0, respectively. The main algorithm update for the C6.1 DT algorithm is a revised surface reflectance model for urban areas based on the MYD09 surface reflectance product (Gupta et al., 2016). For land, if there are more than 50% coastal pixels or 20% water pixels in the retrieval box, QA = 0. The Expected Error (EE) for DT retrievals at the 10-km spatial resolution is [± (0.05 + 15%)] over land (Levy et al., 2013).

The Enhanced DB algorithm (Hsu et al., 2013) is used to produce the DB dataset over land only. It allows for aerosol retrievals over both dark-target and bright surfaces with the deep-blue channels. The surface reflectances for these channels are determined by the three following approaches: (i) dynamic surface reflectance models for vegetated surfaces; (ii) a pre-calculated surface reflectance database for arid/semi-arid surfaces; and (iii) a combination of the above two approaches for urban/built-up and transitional regions. The aerosol types are assumed to be a function of location and season. The main algorithm updates and bug fixes for the C6.1 DB algorithm include (1) heavy smoke detection to address some over-screening while minimizing true cloud contaminations, (2) artifact reduction over heterogeneous terrains, (3) improved surface modeling in elevated terrains, and (4) bug fixes and updated regional/seasonal aerosol models. The updated EEs for DB retrievals are approximately [± (0.03 + 21%)] for arid path retrievals and [± (0.03 + 18%)] for vegetated path retrievals, respectively.

Due to the different assignments of underlying surfaces, pixel selections, aerosol type updates, and other aspects in the DT and DB algorithms, a new combined DT and DB (DTB) dataset was produced to improve the data coverage over land based on MODIS-derived monthly NDVI products. The merge uses a simple approach that leverages the strengths of the two aerosol retrieval algorithms. The DTB product is created as follows: (i) If NDVI > 0.3, use DT retrievals; (ii) if NDVI < 0.2, use DB retrievals; (iii) if 0.2 ≤ NDVI ≤0.3, use the average of DT and DB retrievals or whichever one passes the high-quality assurance (QA = 3 for DT and QA ≥ 2 for DB) (Levy et al., 2013). However, our previous study illustrated that DTB products have almost the same annual mean spatial distributions as DT products over most land areas, except for deserts, arid, and semi-arid areas (Wei et al., 2019). The main reason is that the maximum-value synthetic monthly NDVIs are generally higher than 0.3, especially in summer and autumn over most continental areas (Fig. 1). Compared with DT products, DTB products underperform in most selected regions and at about half of the sites. The DB algorithm generally outperforms the DT algorithm in medium-to densely vegetated areas, suggesting that it is not always appropriate to merge these two datasets using fixed NDVI thresholds (Wei et al., 2019). The objective of this study is to explore a new merging method that considers various factors (i.e., land use, elevation, and aerosol type) to improve the data coverage and reduce the estimation uncertainties in the official C6.1 DTB products.

2. Data sources

In this paper, the latest released Terra and Aqua MODIS C6.1 Level 2 daily swath aerosol products at the spatial resolution of 10 km (MxD04_L2) from 2013 to 2017 over land are collected. Retrievals at 550 nm passing the high-quality assurance for DT (QA = 3), DB (QA ≥ 2), and combined DT and DB (denoted as "DTB0", QA = 3) products are selected. Terra and Aqua MODIS monthly synthetic NDVI products (MxD13C2) and the combined annual land use product (MCD12C1) at 0.5° × 0.5° horizontal resolutions are also collected. For the land cover, the International Geosphere-Biosphere Programme (IGBP) with the seventeen-class scheme is selected and re-classed to six main land use types: forest, grassland, cropland, urban, bare land, and water. The Shuttle Radar Topography Mission (SRTM) 90-m resolution DEM data is used to provide the surface attitude and calculate the surface relief. For validation, newly updated Aerosol Robotic Network (AERONET) Version 3 Level 2.0 AOD ground measurements that have undergone further cloud screening and quality control at 286 sites over land are selected (Smirnov et al., 2000; Holben et al., 2001; Giles et al., 2019; Wei et al., 2019). The 550-nm AOD measurements are interpolated using the Ångström algorithm (Sun et al., 2016b; Wei and Sun, 2017; Wei et al., 2017, 2018a, 2018b, 2019). For comparison, the average value within a sampling window (3 × 3 pixels, at least 3 out of 9 pixels available) centered on an AERONET site is used as the retrieval (Wei et al., 2018a, 2019). The average of at least two AERONET AOD measurements within 1 h (± 30 min) of the Terra and Aqua overpass times is used as the ground truth (Wei and Sun, 2017; Wei et al., 2018a, 2018b, 2019). Retrieval errors are reported using the mean bias, the percentage of data points falling within the EE (Eq. (1)) for the DT algorithm over land, the mean absolute error (MAE), the root-mean-square error (RMSE), and the data-count ratio (N_{DB}/N_{DT}). Relative differences (RDs, %) are calculated using Eq. (2). Table 1 summarizes the data used in this study.

$$EE = \pm(0.05 + 0.15 * AOD_{AERONET}) \tag{1}$$

$$RD = [(DTB1 - DTB0)/DTB0] \times 100 \tag{2}$$

3. Methodology

Fig. 2 shows DT and DB retrievals as a function of NDVI over land and five land use types from 2013 to 2017. The DT algorithm does not perform as well as the DB algorithm with fewer retrievals falling within the EE envelope and larger positive biases (> 0.05). Also, the number of data samples from the DT algorithm is 3–17 times less than that from the DB algorithm in low-vegetated areas (NDVI < 0.2). However, the performance of the DT algorithm gradually improves as the vegetation coverage increases, and differences in the number of data samples between the two algorithms decrease. However, in general, the DB algorithm performs slightly better than the DT algorithm in vegetated areas over land (Fig. 1a). It is therefore not suitable to solely use DT values in areas with NDVI > 0.3, which is done in the operational merge method. The purpose of this study is to propose a more accurate data merge approach based on the analysis of the strengths and weaknesses of the DT and DB algorithms. In this study, one algorithm will be considered unreliable and discarded if it fails to satisfy at least two of the following three conditions: (1) "good" matching if more than 66% of the data samples fall within the EE envelope (*f*, Levy et al., 2013); (2) "good" estimations if the MAE is less than 0.05; and (3) "successful" retrievals if the data-count ratio (*RN*) is less than 4.

The first test of the algorithms is a land-use test. For forested land (Fig. 2b), two distinct stages are seen. The DT algorithm does not perform as well as the DB algorithm when NDVI < 0.3, i.e., only 34% of the data samples fall within the EE envelope, the bias is higher (~0.09), and there are eight times fewer data samples. In this case, the DB retrievals are selected. However, for NDVI ≥ 0.3, both algorithms perform well (*f* > 75%, MAE < 0.05, and *RN* < 4). Since the DB algorithm overestimates AOD and the DT algorithm tends to underestimate AOD, taking the average of the DT and DB retrievals, if both are available, can reduce the overall bias. If one of the retrievals is missing, the available one is used. For grassland (Fig. 2c), when NDVI < 0.25, the DB retrievals are used because of the algorithm's better performance with a higher *f*, lower MAE, and five times more data samples. For NDVI

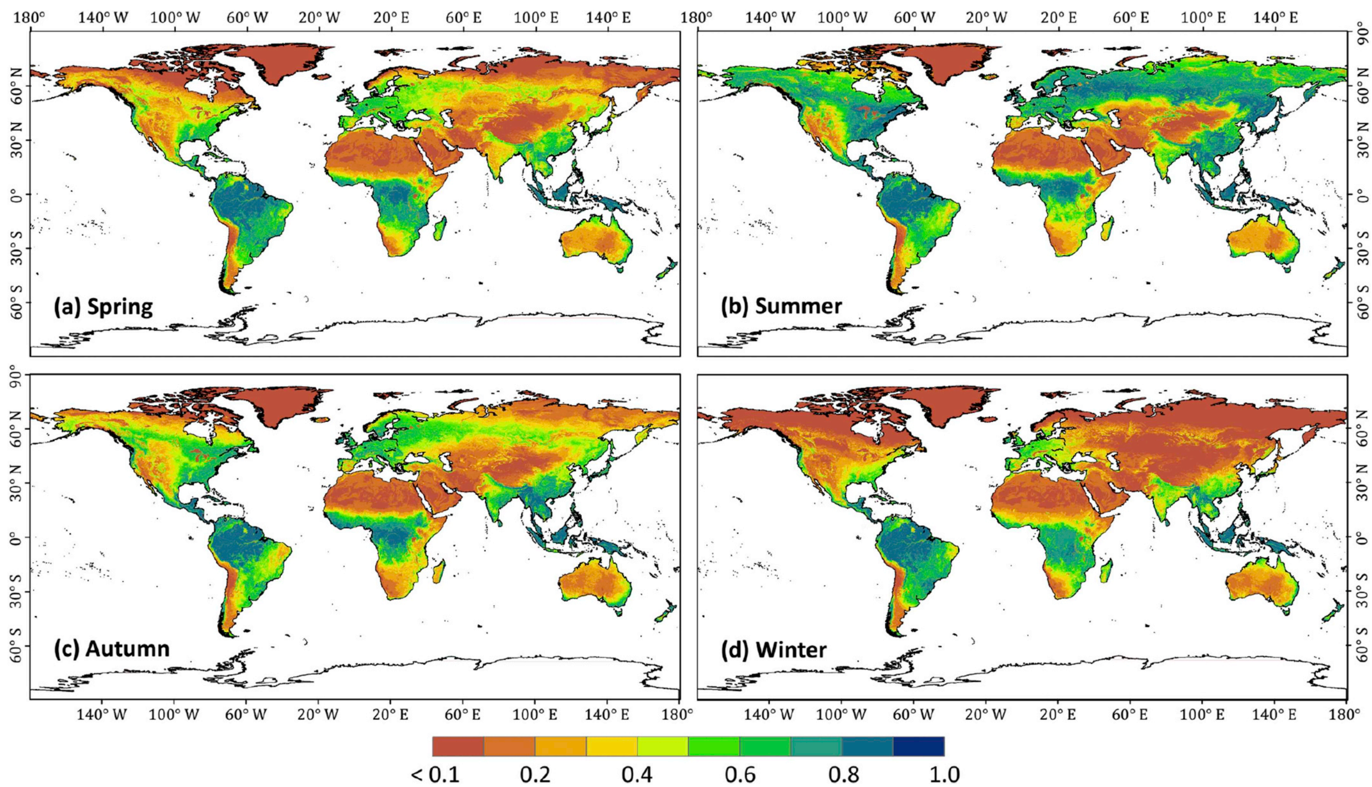

Fig. 1. Seasonally averaged normalized difference vegetation index maps from 2013 to 2017 over land.

≥ 0.25, both algorithms perform well (f > 65%, MAE < 0.02, and RN < 1.5). Again, since the DB algorithm underestimates AOD and the DT algorithm tends to overestimate AOD, the average of the DT and DB retrievals, if both are available, is taken here. For cropland (Fig. 2d), both DT and DB algorithms perform in a similar way over a wide range of NDVI values. Here, the DT algorithm tends to overestimate AOD, and the DB algorithm sometimes underestimates AOD. Thus, the average of the DT and DB retrievals, or the available one, is selected. For urban areas (Fig. 2e), the DT algorithm does not perform as well as the DB algorithm when NDVI < 0.2, i.e., less than 50% of the data samples fall within the EE envelope, the bias is higher (> 0.05), and there are 3–6 times fewer data samples. In this case, only the DB retrievals are used. By contrast, as NDVI increases, the performance of the DT algorithm gradually stabilizes, but AOD is always overestimated. However, the DB algorithm tends to underestimate AOD when 0.2 < NDVI < 0.4 and performs just as well as the DT algorithm when NDVI > 0.4. Unlike the C6 DT algorithm, the C6.1 DT algorithm performs better in urban areas, benefiting from the improved surface reflectance estimation model (Gupta et al., 2016). Therefore, the average of DT and DB retrievals or the available one is selected when NDVI ≥ 0.2. The DT algorithm does not work well over bare land (Fig. 2f). There is an average of 27 times fewer retrievals, a much lower f, and a higher MAE than the DB algorithm. Therefore, the DB retrievals are selected for bare land. DT retrievals are selected for water bodies and oceans because the DB algorithm does not do retrievals over this surface type. In general, a combination of land use types and monthly NDVI values can better reflect the change in surface reflectance. Seasonal changes for different land types can also be considered.

The second test of the algorithms is a surface altitude-relief test (Fig. 3). Both DT and DB algorithms perform well in low-altitude areas (H < 0.8 km) with high percentages and low biases. However, as the surface altitude increases, the performance of the DT algorithm deteriorates (low f and high positive biases) while the DB algorithm still performs well (f > 72% and MAE < 0.03; Fig. 3a). To further explore the effect of altitude changes on the two algorithms, the surface relief (R), a quantitative index for describing the form of the geomorphology, is calculated using the sliding window method:

$$R = H_{max} - H_{min} \tag{3}$$

where R represents the surface relief, and H_{max} and H_{min} represent the maximum and minimum heights, respectively, in area units. Both DT and DB algorithms perform well when R < 0.8, however, with an

Table 1
Data sources used in this study.

Data	Scientific Data Set	Contents	Resolution
MxD04	Optical_Depth_Land_And_Ocean	DT over land (QA = 3)	10 km
	Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate	DB over land (QA ≥ 2)	
	AOD_550_Dark_Target_Deep_Blue_Combined	DTB over land (QA = 3)	
	Aerosol Type Land	Aerosol type	10 km
MxD13C2	NDVI	NDVI	0.5° × 0.5°
MCD12C1	IGBP scheme	Land use cover	0.5° × 0.5°
SRTM	DEM	DEM	90 m
AERONET	Version 3 Level 2.0	Aerosol optical depth	15 min

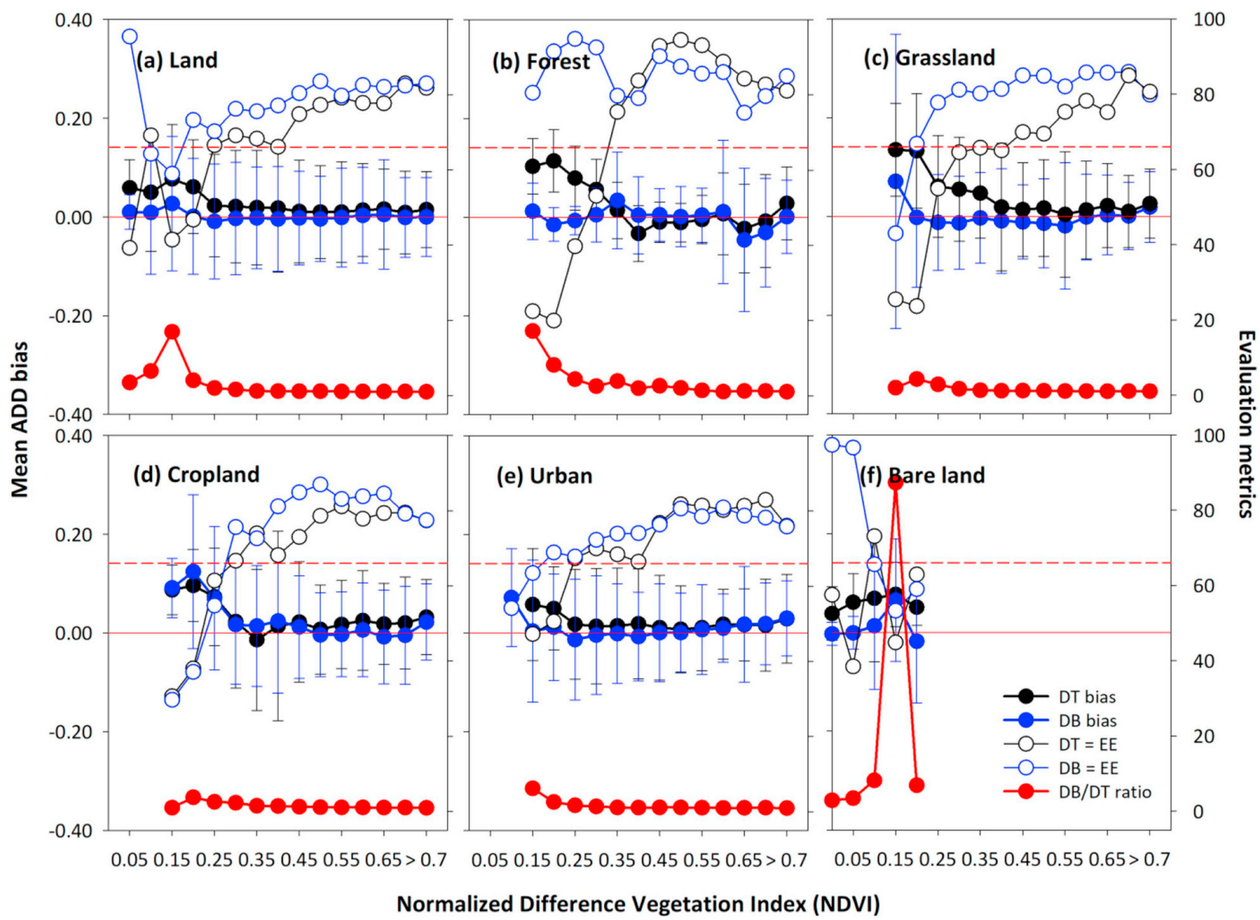

Fig. 2. Mean aerosol optical depth (AOD) bias (black, filled circles for the DT algorithm and blue, filled circles for the DB algorithm), fraction of retrievals matching the expected error (EE, black, open circles for the DT algorithm and blue, open circles for the DB algorithm), and the data-count (DB/DT) ratio (red, filled circles) as a function of NDVI for six land use types. The bias is calculated with respect to AERONET AOD retrievals. The red horizontal solid and dotted lines represent the zero bias (X = 0) and "good" matching lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

increase in surface relief ($0.8 \leq R \leq 2$), the adaptability of the DT algorithm gradually decreases (i.e., decreasing f and increasing positive biases; Fig. 3b). By contrast, the DB algorithm can always perform well due to improvements in artifact reduction and surface modeling in heterogeneous elevated terrains, especially in areas with abrupt topographic changes. Therefore, DB retrievals are chosen over severely rugged areas ($R > 2$).

The last test of the algorithms is an aerosol-type test [Fig. 6c in Wei et al. (2019)]. Both DT and DB algorithms perform well in weakly-to-moderately-absorbing-aerosol-dominated areas (Wei et al., 2018b,

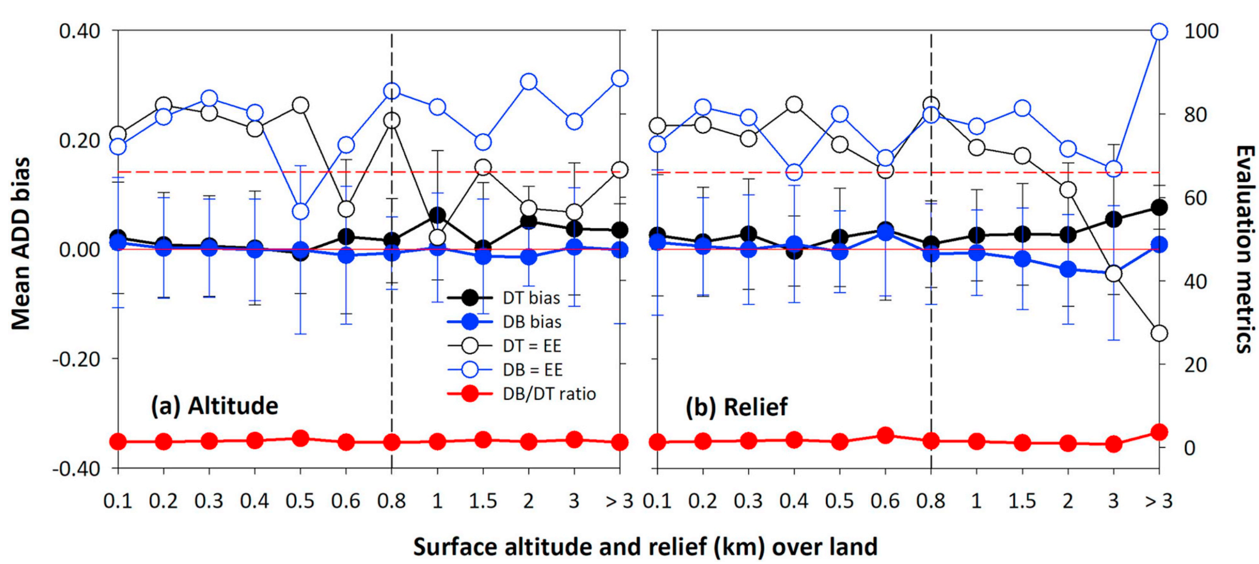

Fig. 3. Same as Fig. 2 but for (a) surface altitude and (b) surface relief.

2019). Therefore, the average of DT and DB retrievals, or the available one, is used in this case. However, the DT algorithm performs much worse than the DB algorithm in continental and dust-aerosol-dominated areas. DB retrievals are selected in this case. The DB algorithm underestimates AOD while the DT algorithm always overestimates AOD in strongly-absorbing-aerosol-dominated areas. In this case, the average of DT and DB retrievals, or the available one, is selected to reduce the average bias and improve the data quality. Note that this test is optional because these three dominant aerosol types cover a small part of land areas and aerosol-type effects may be related to surface brightness (Wei et al., 2019). Further research on this issue needs to be done.

4. Results and discussion

4.1. Site-scale validation and comparison

The operational Terra and Aqua C6.1 DTB0 and new merged DT and DB products (denoted as DTB1) products at 279 selected AERONET ground-based observation sites (with at least 20 matchups) around the world are evaluated based on four main evaluation metrics: (a) the number of data samples (N), (b) the percentage of data samples falling within the EE envelope, (c) MAE, and (d) RMSE (Fig. 4). To better show the differences between the two products at individual-site scales, the relative differences of the four metrics are calculated for each site, where warm colors indicate increased relative differences, cool colors indicate decreased relative differences, and the color variations represent the magnitudes of the relative differences. The black dots represent equal performances at these sites. The Terra and Aqua DTB1 products have more data samples than the operational Terra and Aqua DTB0 products at 255 (Terra) and 252 (Aqua) sites. Also, 46% and 59% of these sites (for Terra and Aqua, respectively) show a noticeable increase in the number of data samples (by greater than 20%), especially those sites located in North America, Europe, and East Asia, with larger relative differences (> 50%). The increase in the number of data samples for the Aqua DTB1 product appears to be greater than that for the Terra DTB1 product at most sites (Fig. 4a–i and 4a-ii). These results suggest that the new merged DTB1 products significantly increase the spatial and temporal coverage at the site scale.

Regarding the percentage of data samples falling within the EE envelope (Fig. 4b–i and b-ii), 63% and 53% of the sites show positive relative differences for the Terra and Aqua DTB1 products compared with the Terra and Aqua DTB0 products, respectively. Twenty-five percent and 18% of the sites show the greatest improvements and the percentages of data samples within the EE envelope increase by 10% to greater than 50% for the Terra and Aqua DTB0 products, respectively. Note that there are 70 and 94 sites with slightly decreasing percentages (< 10%) mainly due to the increase in the number of data samples. In general, the new merged DTB1 products are improved with increasing percentages of data samples matching the EEs at most sites compared with DTB0 products.

The MAEs (Fig. 4 c-i and c-ii) and RMSEs (Fig. 4 d-i and d-ii) of the Terra and Aqua DTB1 products at most sites are noticeably reduced compared with the DTB0 products. Especially at the North American, South American, and European sites, the MAEs and RMSEs are decreased by 40% (Terra) and 20% (Aqua). In general, the DTB1 products perform better than the DTB0 products at 53–59% and 51–55% of the selected sites in terms of MAE and RMSE, respectively. Both products perform equally well at 8–12% of the sites located in major arid and semi-arid areas. There are small negative relative differences within 10% in terms of MAE at 16–18% of the sites and RMSE at 22–23% of the sites, likely due to more data samples. Overall, results suggest that the Terra and Aqua DTB1 products are improved and more accurate than the DTB0 products with significantly greater numbers of data samples, higher percentages of data samples within the EE envelope, and lower estimation uncertainties (i.e., MAE and RMSE) at the site scale.

4.2. Continent-scale validation and comparison

This section focuses on validations and comparisons between Terra and Aqua DTB0 and DTB1 products on a continental scale. Land surfaces were divided into four main continents: Europe (74 sites), the Americas (i.e., North and South America, 119 sites), Asia (69 sites), and Africa (24 sites). The DTB0 and DTB1 retrievals were validated against AERONET AOD measurements from all available sites on each continent.

4.2.1. Europe

Fig. 5 shows density scatter plots of the validation and comparison between DTB0 and DTB1 products for Terra and Aqua at the 74 sites located in Europe. The black solid and dotted lines represent the 1:1 line and EE envelopes, respectively. The percentage of data samples falling within, above, and below the EE are given by = EE, > EE, and < EE, respectively. AODs are generally lower than 0.5 which indicates good air quality in Europe. The Terra and Aqua DTB1 products significantly improve the spatiotemporal coverage with increasing numbers of data samples (26% for Terra and 36% for Aqua) compared with DTB0 products. The main reason is that the DTB0 products mostly adopt DT values in most parts of Europe due to the relatively high vegetation coverage there (Wei et al., 2018a, 2019). However, in these areas, the DB algorithm has more accurate aerosol retrievals, and our new approach considers both DT and DB retrievals over a large range of NDVI values which increases the number of data samples. The percentages of data samples falling within the EE envelope increases by ~11% and 6%, and the average MAE and RMSE values decrease by 19% and 17%, and 17% and 16% for Terra and Aqua DTB1 products, respectively, compared with DTB0 products.

An equal-number-collection validation and comparison was performed (Table 2). A total of 12,433 and 10,214 data samples from Terra and Aqua DTB0 and DTB1 products, respectively, were matched. Compared with the DTB0 products, the Terra and Aqua DTB1 products have a greater percentage of data samples falling within the EE envelope (~10% and 5%, respectively), decreased MAEs (14% and 9%, respectively), RMSEs (11% and 6%, respectively), and biases (38% and 23%, respectively). Thirty-four hundred eight-six and 3956 unique DTB1 retrievals were obtained from the Terra and Aqua products, respectively. About 79–84% of the retrievals met the requirements of the EE and had low MAE and RMSE values less than 0.044 and 0.066, respectively. These results suggest that the DTB1 products significantly increase the spatiotemporal coverage and improve the data quality over Europe.

4.2.2. The Americas

Fig. 6 shows density scatter plots of the validation and comparison between DTB0 and DTB1 products for Terra and Aqua at 119 sites located in North and South America. The air quality here is slightly worse than that in Europe with overall low AOD values below 0.8 on most days. Moreover, the DTB0 products for the Americas have high percentages falling within the EE envelope and close MAE and RMSE values, similar to Europe. Terra and Aqua DTB1 products have an increased percentage of data samples (21% for Terra and 34% for Aqua) compared with DTB0 products. The main reason is that like Europe the DTB0 algorithm mainly selects DT retrievals over most of the Americas (Wei et al., 2018a, 2019). Moreover, the percentage of data samples falling within the EE envelopes are overall increased with decreasing MAE values.

For an equal-number-collection comparison, 20,700 and 15,471 common points between Terra and Aqua DTB0 and DTB1 products were collected (Table 3). In general, the percentages of data samples falling within the EE envelope for Terra and Aqua DTB1 retrievals increase by 5% and 3%, MAE values decrease by 11% and 8%, and RMSE values decrease by 6% and 8%, respectively. The average biases are also

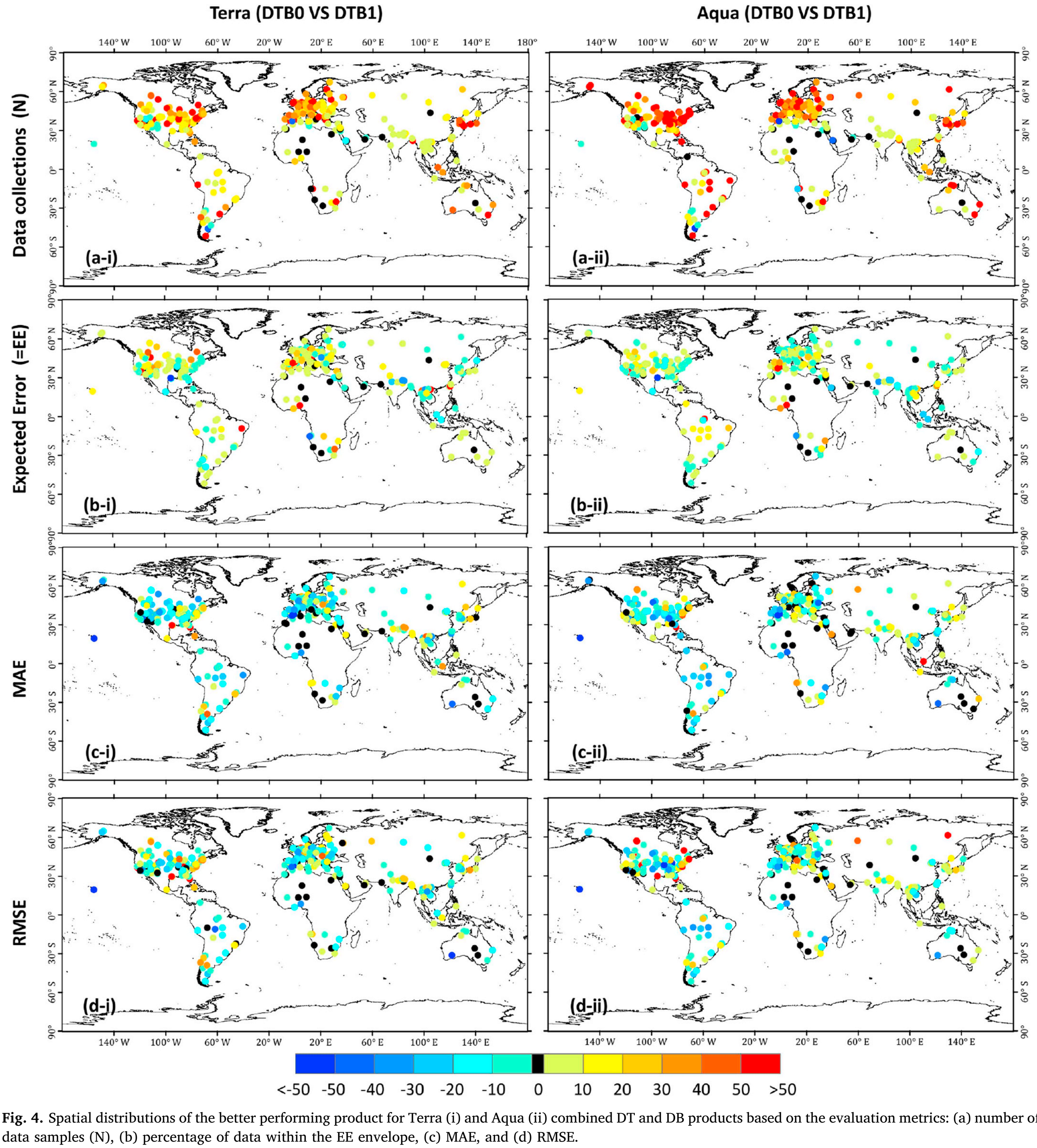

Fig. 4. Spatial distributions of the better performing product for Terra (i) and Aqua (ii) combined DT and DB products based on the evaluation metrics: (a) number of data samples (N), (b) percentage of data within the EE envelope, (c) MAE, and (d) RMSE.

reduced and are closer to 0. Forty-eight hundred sixty-four and 5675 unique retrievals were collected from the Terra and Aqua DTB1 products. They agreed well with the AEROENT AOD measurements with percentages of data samples falling within the EE envelope of 75.43% and 81.20%, MAEs of 0.052 and 0.043, and RMSEs of 0.106 and 0.100, respectively. These results suggest that the DTB1 products can provide wider spatiotemporal coverage and are more accurate than the DTB0 products over North and South America.

4.2.3. Asia

Aerosol loadings over Asian sites are approximately three times than that over Europe under most conditions, suggesting severe air pollution (Fig. 7). Complex and diverse surface structures and changing aerosol compositions lead to overall poorer aerosol estimations with lower fractions of data samples falling within the EE envelope and approximately two times larger MAE and RMSE values in Asia than in Europe and America. Remote sensing aerosol retrievals in this region are thus

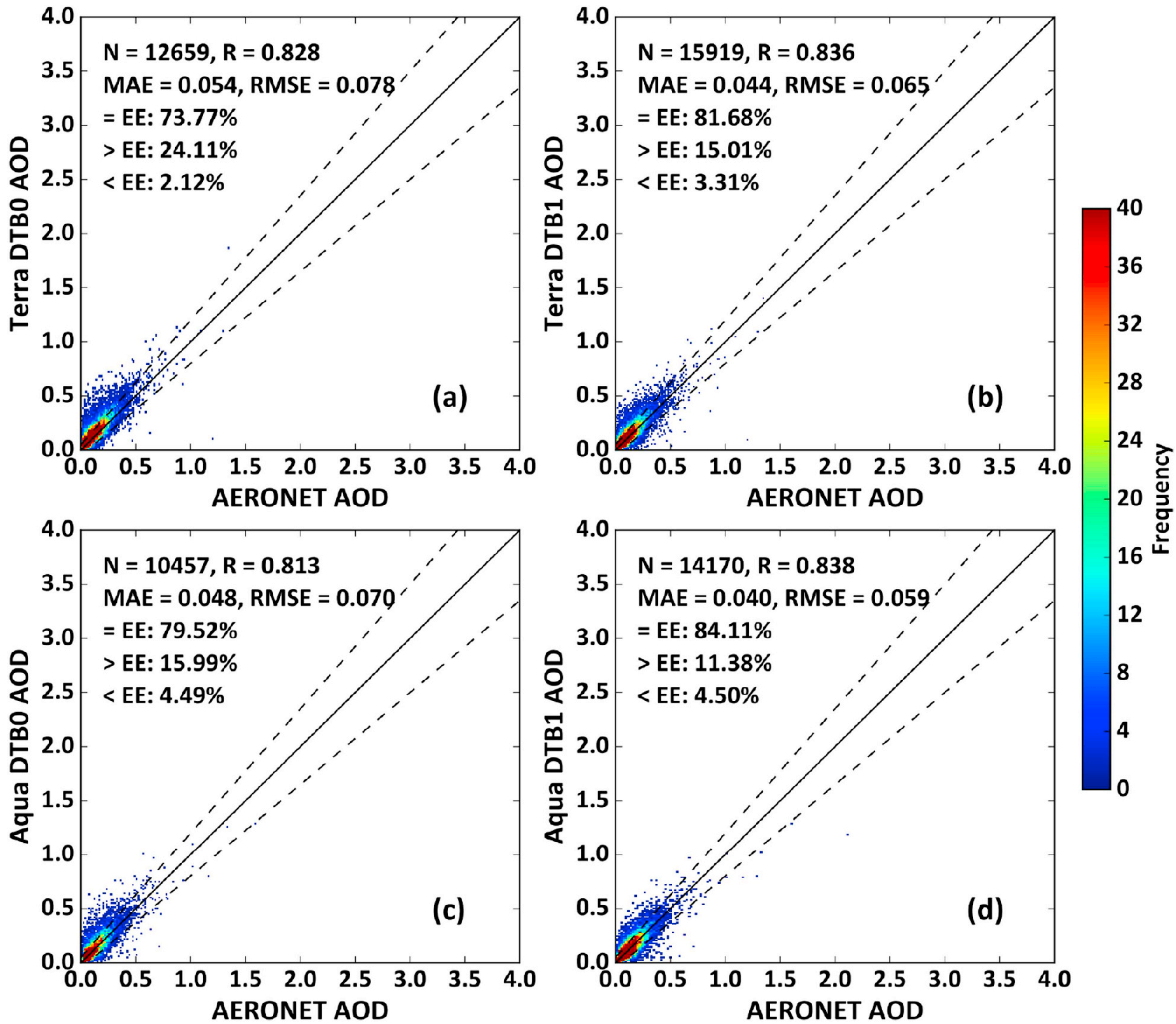

Fig. 5. Density scatter plots of Terra and Aqua MODIS C6.1 DTB0 and DTB1 AODs as a function of AERONET AOD measurements over Europe from 2013 to 2017. The black solid line is the 1:1 line, and the dashed lines outline the EE envelope.

Table 2
Statistical summary of common and unique retrievals for Terra and Aqua C6.1 DTB0 and DTB1 products over Europe from 2013 to 2017. In each row, the better performance of two merged products by each metric is indicated in bold.

Europe	Terra			Aqua		
Metrics	DTB0	DTB1	Unique	DTB0	DTB1	Unique
Sample size (N)	12433	12433	3486	10214	10214	3956
Within EE (=EE, %)	74.78	**82.19**	79.86	80.73	**84.32**	83.59
MAE	0.051	**0.044**	0.044	0.045	**0.041**	0.037
RMSE	0.073	**0.065**	0.066	0.065	**0.061**	0.056
Bias	0.034	**0.021**	0.006	0.013	**0.010**	0.002

challenging to make, especially in East and South Asia (Wei and Sun, 2017; Wei et al., 2017, 2018b). Compared with the DTB0 products, data counts increase by 12% and 13%, respectively, for the Terra and Aqua DTB1 products. In general, compared with the DTB0 products, the DTB1 products are overall improved with increasing percentages of data samples falling within the EE envelope and decreasing estimation uncertainties.

For an equal-number-collection comparison, 14,465 and 12,309 common points between Terra and Aqua DTB0 and DTB1 products were collected (Table 4). In general, the DTB1 products are slightly better than the DTB0 products with overall improved metrics (by within 5%) and mean biases closer to 0. Eighteen hundred thirty-two and 1765 unique matchups were collected from the Terra and Aqua DTB1 products. They agreed well with the AEROENT AOD measurements with percentages of data samples falling within the EE envelope of 60–74%. Overall, the similar performances of the DTB0 and DTB1 algorithms are mainly attributed to the brighter surfaces (mainly for urban, arid, and semi-arid areas) in Asia than in Europe given that the data merging is based on the same approach. The main differences in the merge approach only occur in those areas with rich vegetation coverage (i.e., Southeast Asia) or for a few months of the year (i.e., summer, autumn). These results suggest that the DTB1 products can improve the data coverage and generally decrease estimation errors compared with the DTB0 products over Asia.

4.2.4. *Africa*

The aerosol loading over Africa is approximately half that over Asia (Fig. 8). Northern Africa and southern Africa have different surface types. Northern Africa is covered by deserts and sparse vegetation, and southern Africa is more vegetated. Desert dust episodes occur frequently in northern Africa, complicating the aerosol retrieval process (Hsu et al., 2004; Wei et al., 2018b). Of the four continents considered in this study, the lowest percentage of retrievals falling within the EE

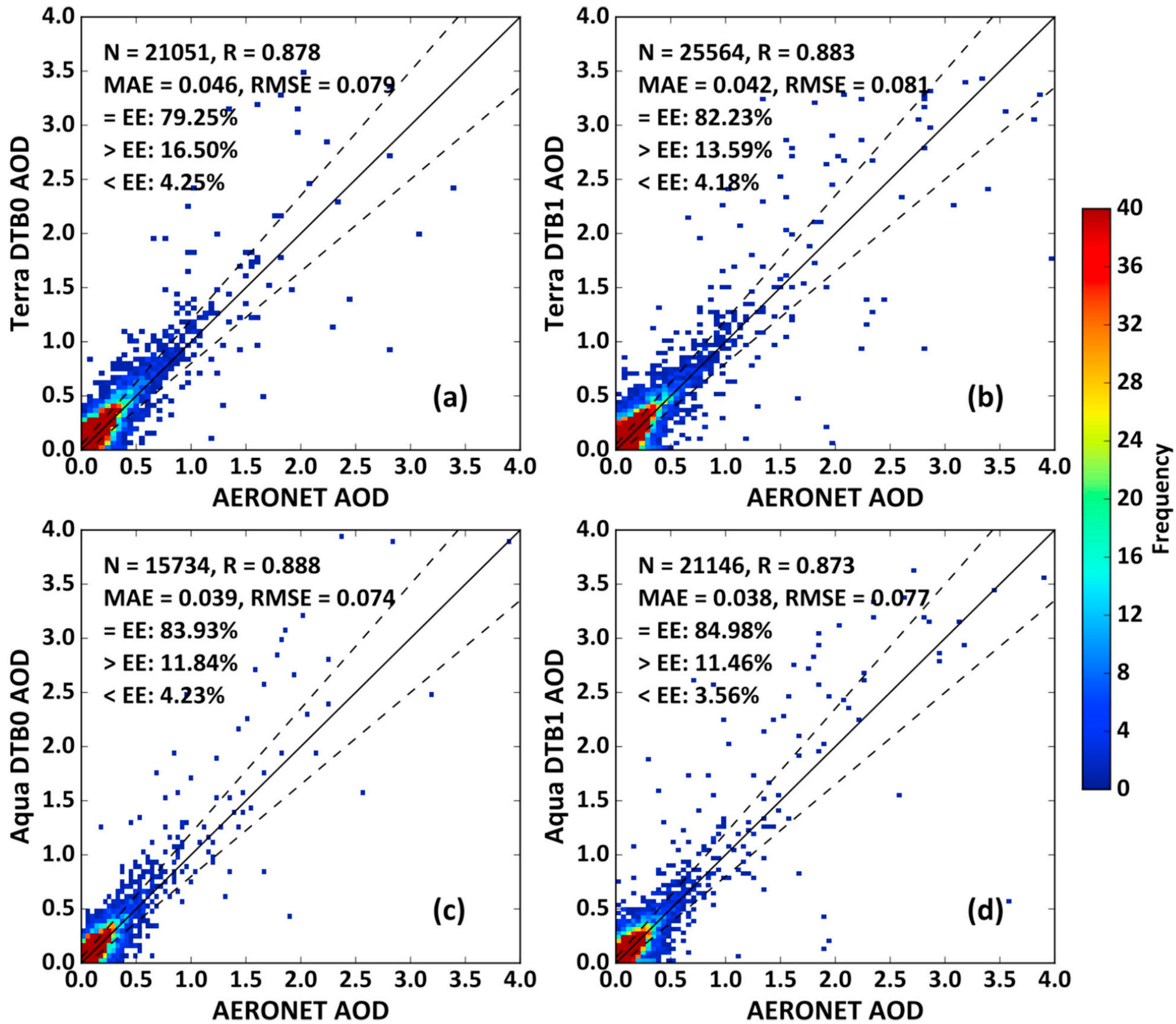

Fig. 6. Same as Fig. 5 but for North and South America.

Table 3
Same as Table 2 but for North and South America.

America	Terra			Aqua		
Metrics	DTB0	DTB1	Unique	DTB0	DTB1	Unique
Sample size (N)	20700	20700	4864	15471	15471	5675
Within EE (=EE, %)	79.65	**83.82**	75.43	84.26	**86.37**	81.20
MAE	0.045	**0.040**	0.052	0.039	**0.036**	0.043
RMSE	0.079	**0.074**	0.106	0.073	**0.067**	0.100
Bias	0.019	**0.012**	0.022	0.009	**0.007**	0.018

envelope occurs in Africa. Because of the low vegetation coverage, the DTB1 products perform as well as the DTB0 products at approximately one-third of the sites due to the same merge approach used. In general, the number of data samples from the DTB1 products is 4% more than that from the DTB0 products. The data quality of the DTB1 products is overall improved with an increasing percentage of the data samples falling within the EE envelope and decreasing MAE and RMSE values.

For an equal-number-collection comparison, 7453 and 6638 common retrievals between Terra and Aqua DTB0 and DTB1 products were collected (Table 5). The metrics of the DTB0 products are overall better than those of the DTB1 products. Three hundred fifty-nine and 307 unique matchups were collected from the Terra and Aqua DTB1 products. They agreed well with the AEROENT AOD measurements with percentages of data samples falling within the EE envelope of 66–68%. These results suggest that the DTB1 products can improve the data coverage and generally decrease estimation errors compared with the DTB0 products over Africa.

4.3. Global-scale validation and comparison

This section focuses on comparisons at the global scale. For this purpose, Terra and Aqua DTB0 and DTB1 retrievals across all 286 available sites over land are collected and validated against AERONET AOD measurements from 2013 to 2017 (Fig. 9). The number of data samples increases from 56,357 to 66,219 for the Terra DTB1 product and 45,914 to 56,970 for the Aqua DTB1 product, which is 17% and 24% more than for the corresponding DTB0 products, respectively. The percentages of matchups falling within the EE envelope increase by 4%–5%, and MAEs decrease by 8%–9% and RMSEs decrease by 4%–5%. In general, the data coverage significantly increases, benefiting from the integrated use of both DT and DB retrievals over a wide range of NDVI values over land.

For an equal-number-collection comparison, 55,597 and 45,181 common retrievals between Terra and Aqua DTB0 and DTB1 products were collected (Table 6). Compared with the DTB0 products, the Terra

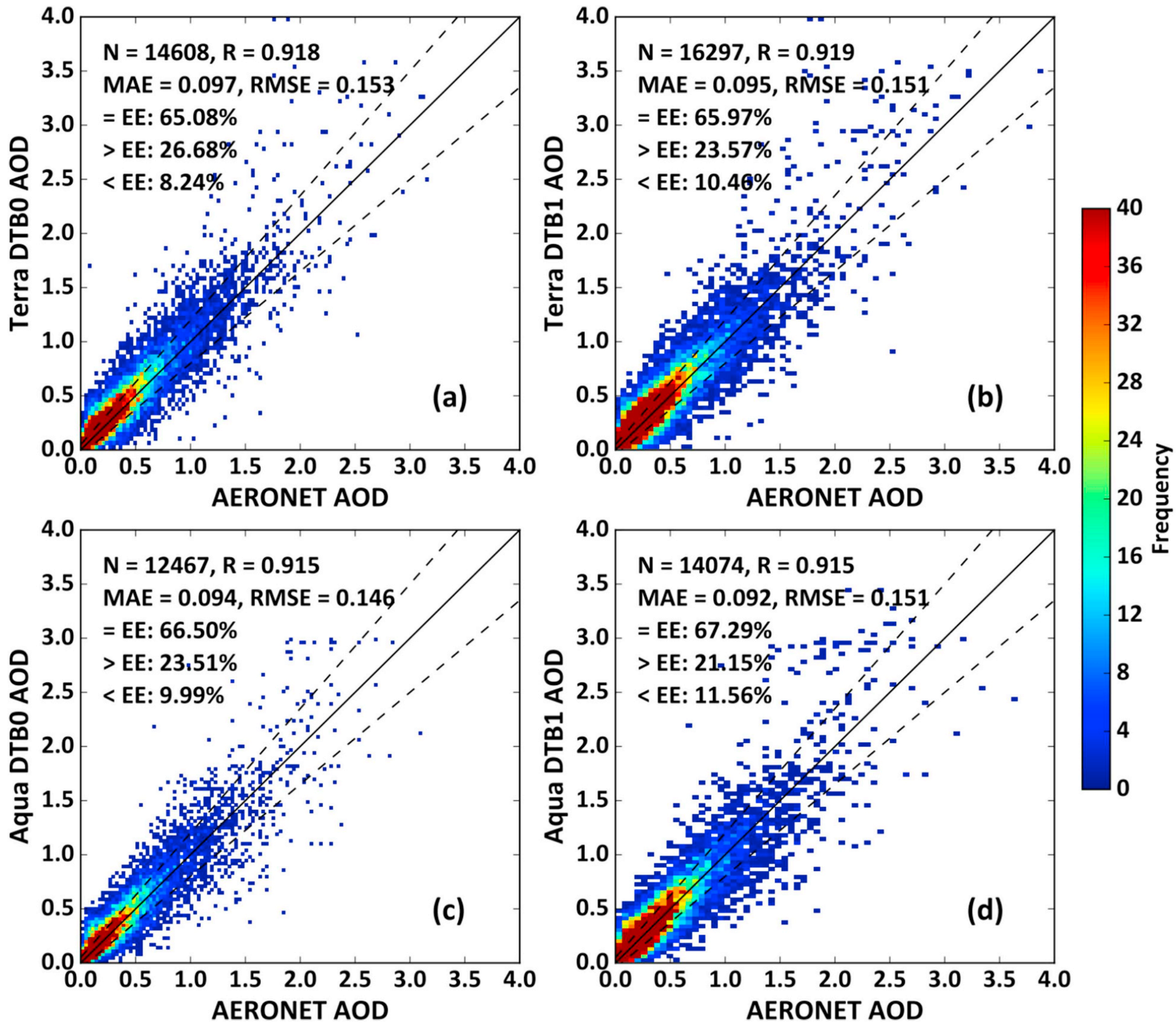

Fig. 7. Same as Fig. 5 but for Asia.

Table 4
Same as Table 2 but for Asia.

Asia	Terra			Aqua		
Metrices	DTB0	DTB1	Unique	DTB0	DTB1	Unique
Sample size (N)	14465	14465	1832	12309	12309	1765
Within EE (=EE, %)	65.03	**65.85**	66.92	66.38	**66.41**	73.48
MAE	0.097	**0.095**	0.094	0.094	**0.093**	0.086
RMSE	0.152	**0.148**	0.173	0.147	**0.145**	0.183
Bias	0.038	**0.024**	0.035	0.024	**0.015**	0.020

and Aqua DTB1 products have greater percentages of data samples falling within the EE envelope and decreases in MAEs and RMSEs (by 2% and 8%, respectively). Compared with the DTB0 products, mean biases decreased from 0.025 to 0.016 and from 0.013 to 0.010 for the Terra and Aqua DTB1 products. Ten thousand six hundred twenty-two and 11,789 unique points were collected from Terra and Aqua DTB1 products. The percentages of data samples falling within the EE envelope are 75.18% and 80.51% with MAE values of 0.058 and 0.049, and RMSE values of 0.111 and 0.107, respectively. Overall, the DTB1 products are more robust and accurate than the DTB0 products with significantly increasing data coverage and decreasing estimation uncertainties over land.

4.4. Validation and comparison under varying surface conditions

4.4.1. Underlying surfaces

Fig. 10a and b shows the validation and comparison between DTB0 and DTB1 products for Terra and Aqua as a function of NDVI. For sparse-vegetation-coverage areas (NDVI < 0.2), the DTB1 products perform almost equally well with relative differences close to 0 due to the same merge approach used. For medium-vegetation-coverage areas (0.2 ≤ NDVI ≤ 0.6), the DTB1 products perform better than the DTB0 products with more data samples (12–28% and 15–46% more), greater percentages of data samples falling within the EE envelope (by 2–8% and 1–7%), decreasing MAEs (by 2–14% and 3–17%), and decreasing RMSEs (by 3–9% and 2–11%) for Terra and Aqua, respectively. For densely vegetated areas (NDVI > 0.6), the number of data samples for Terra and Aqua increases by 18–22% and 24–30%, respectively, and the percentage of data samples falling within the EE envelope increases with decreasing MAEs. In general, the DTB1 products significantly increase the data coverage and overall improve the data quality over a large range of NDVI values.

Fig. 10c and d shows the relative differences in performance between the Terra and Aqua DTB0 and DTB1 products for four main land use types including forest, grassland, cropland, and urban areas. For forested land, the number of data samples increases by 18% and 29%,

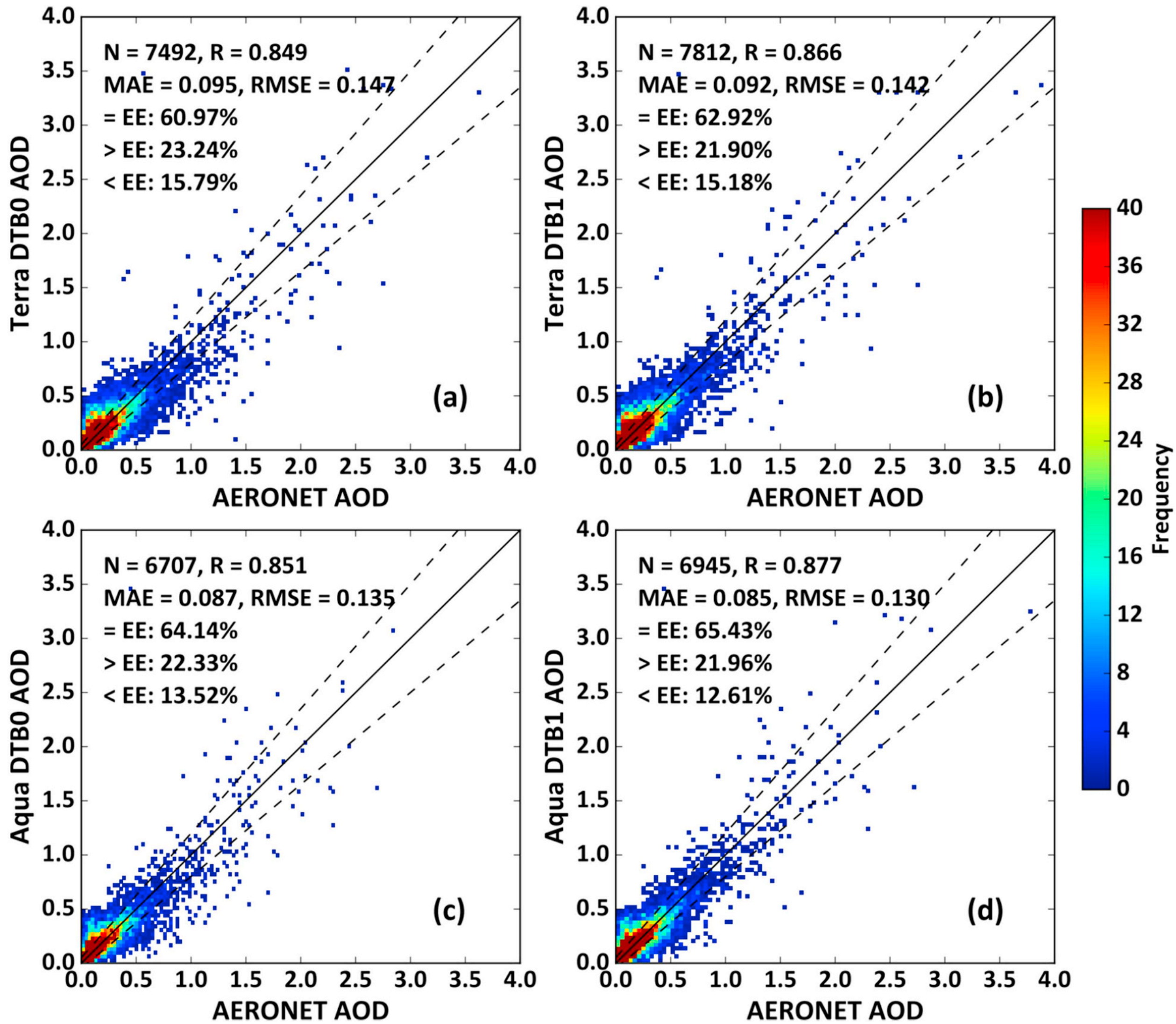

Fig. 8. Same as Fig. 5 but for Africa.

Table 5
Same as Table 2 but for Africa.

Africa	Terra			Aqua		
Metrics	DTB0	DTB1	Unique	DTB0	DTB1	Unique
Sample size (N)	7453	7453	359	6638	6638	307
Within EE (=EE, %)	60.97	**62.75**	66.30	64.07	**65.35**	67.10
MAE	0.095	**0.092**	0.088	0.088	**0.084**	0.093
RMSE	0.146	**0.142**	0.137	0.136	**0.129**	0.154
Bias	0.002	**0.002**	−0.012	0.006	**0.006**	0.013

the percentages of data samples falling within the EE envelope increase by 2%, and the MAEs decrease by 2% and 5% for the Terra and Aqua DTB1 products compared with those of the DTB0 products, respectively. For grassland, the number of data samples increases by 16% and 25%, the percentages of data samples falling within the EE envelope increase by 10% and 8%, the MAEs decrease by 14% and 16%, and the RMSEs decrease by 7% and 6%, respectively. For cropland, Terra and Aqua DTB1 products show increases in the number of data samples (by 19% and 28%), increases in the percentages of data samples falling with the EE envelope (by 8% and 5%), decreasing MAEs (by 13% and 12%), and decreasing RMSEs (by 7% and 8%) compared with the DTB0 products. For urban areas, Terra and Aqua DTB1 products show increases in the number of data samples (by 23–29%), increases in the percentage of data samples falling with the EE envelope (by 1–2%), decreasing MAEs (by 5%), and decreasing RMSEs (by 1–3%) compared with the DTB0 products. In general, the DTB1 products significantly increased the spatiotemporal coverage and are overall better than the DTB0 products for all land use types considered here.

4.4.2. Elevated terrains

This section validates and compares the performances of the two merged aerosol products over varying elevated terrains. Fig. 11a and b shows the relative differences between Terra and Aqua DTB0 and DTB1 products as a function of surface altitude over land. For low-altitude areas (H < 800 m), the Terra and Aqua DTB1 number of data samples increases by 12–23% and 11–34%, the percentages of data samples falling with the EE envelope increases by 3–22% and 1–19%, the MAEs decrease by 5–25% and 4–26%, and the RMSEs decrease by 3–18% and 2–16% compared with DTB0 products. For high-altitude areas (H ≥ 800 m), the number of data samples increases modestly. However, the Terra and Aqua DTB1 percentages of data samples falling within the EE envelope increases by 2–26% and 1–10%, and the MAEs decrease by 1–19% and 2–11%, compared with the DTB0 products.

Fig. 11c and d shows the relative differences in performance between Terra and Aqua DTB0 and DTB1 products as a function of surface relief. For flat terrains (R < 800 m), the number of data samples significantly increase by 10–39%, the percentages of data samples falling

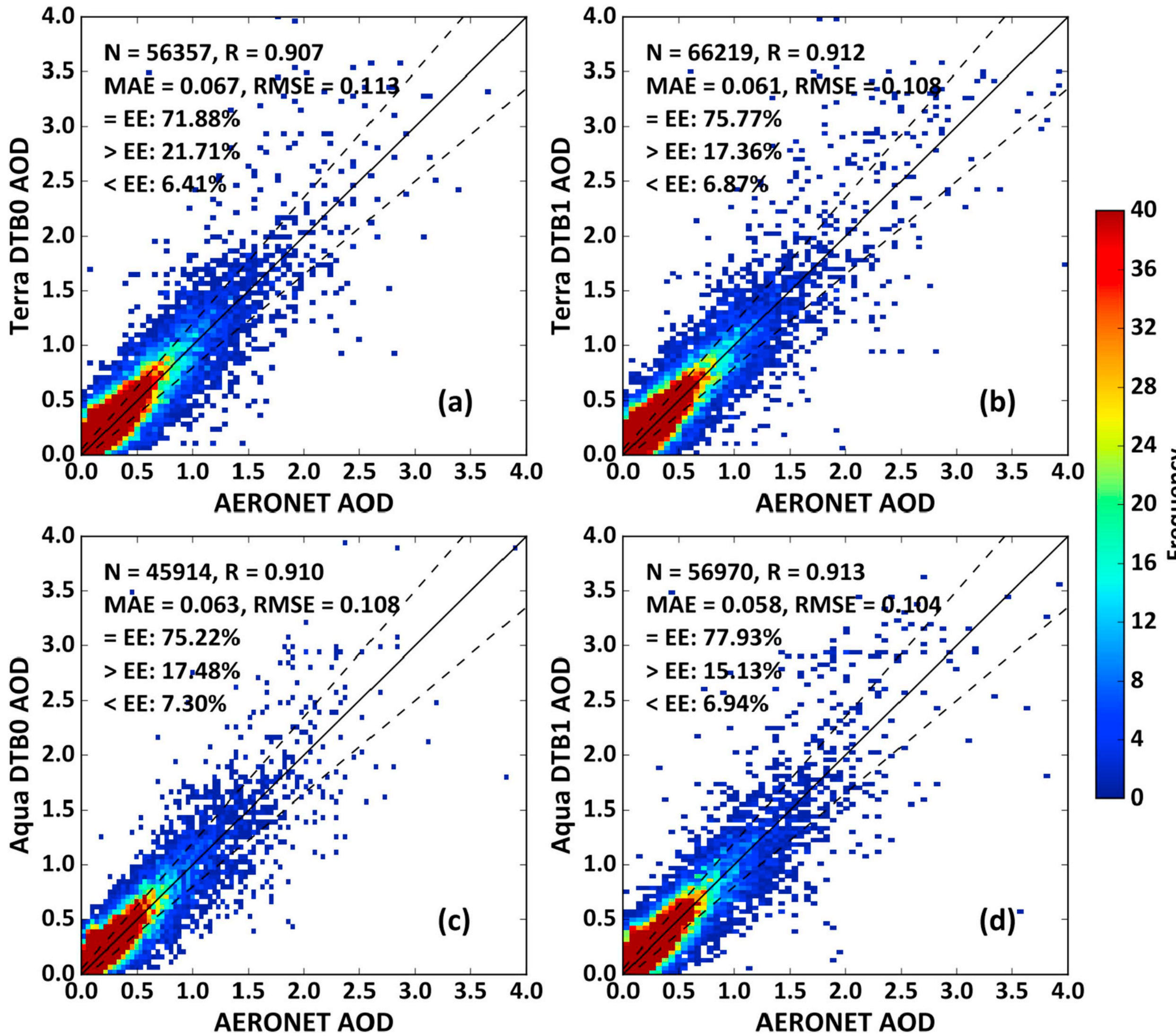

Fig. 9. Same as Fig. 5 but for the globe.

Table 6
Same as Table 2 but for the globe.

Global	Terra			Aqua		
Metrics	DTB0	DTB1	Unique	DTB0	DTB1	Unique
Sample size (N)	55597	55597	10622	45181	45181	11789
Within EE (=EE, %)	72.21	**75.88**	75.18	75.54	**77.25**	80.51
MAE	0.067	**0.062**	0.058	0.063	**0.060**	0.049
RMSE	0.112	**0.107**	0.111	0.108	**0.104**	0.107
Bias	0.025	**0.016**	0.018	0.013	**0.010**	0.013

with the EE envelope increase by 1–8%, the MAEs decrease by 2–13%, and the RMSEs decrease by 1–12% for the Terra and Aqua DTB1 products, respectively, compared with the DTB0 products. For rugged terrains ($R \geq 800$ m), the number of data samples increases modestly. The Terra and Aqua DTB1 percentages of data samples falling within the EE envelope increases by 5–18%, and the MAE and RMSE decrease by 1–19% and 2–11%, respectively, compared with the DTB0 products. This is mainly attributed to the artifact reduction and improved surface modeling of heterogeneous, elevated terrains in the C6.1 DB algorithm. In general, the DTB1 algorithm has significantly increased the spatial and temporal coverage and improved the overall quality of AOD retrievals over varying elevated terrains compared with the DTB0 algorithm.

5. Summary and conclusions

This is a follow-on study aimed at increasing the spatiotemporal coverage and improving the data quality of operational MODIS C6.1 merged DT and DB (DTB0) products. Improved merge schemes are developed based on the land-use-type test, the surface-relief test, and the aerosol-type test. (1) For forested land, use DB retrievals when NDVI $<$ 0.3; use the average of DT and DB retrievals, if available, and if not available, either the DT or DB retrieval when NDVI $\geq$ 0.3. For grassland, use DB retrievals when NDVI $<$ 0.25; use the average of DT and DB retrievals, if available, and if not available, either the DT or DB retrieval when NDVI $\geq$ 0.25. For cropland, use the average of DT and DB retrievals, if available, and if not available, either the DT or DB retrieval for all NDVI values. For urban areas, use the DB retrievals when NDVI $<$ 0.2; use the average of DT and DB retrievals, if available, and if not available, either the DT or DB retrieval when NDVI $\geq$ 0.2. For bare land, use the DB retrievals. For water bodies, use the DT retrievals. (2) For surface reliefs greater than 2, use the DB retrievals. (3) Use the average of DT and DB retrievals, if available, and if not available, either the DT or DB retrieval in the presence of strongly, moderately, and weakly absorbing aerosols. For continental and dust-aerosol-dominated areas, use the DB retrievals. For this merge approach, only DT (QA = 3) and DB (QA $\geq$ 2) AOD retrievals at 550 nm passing the recommended quality assurance tests are used.

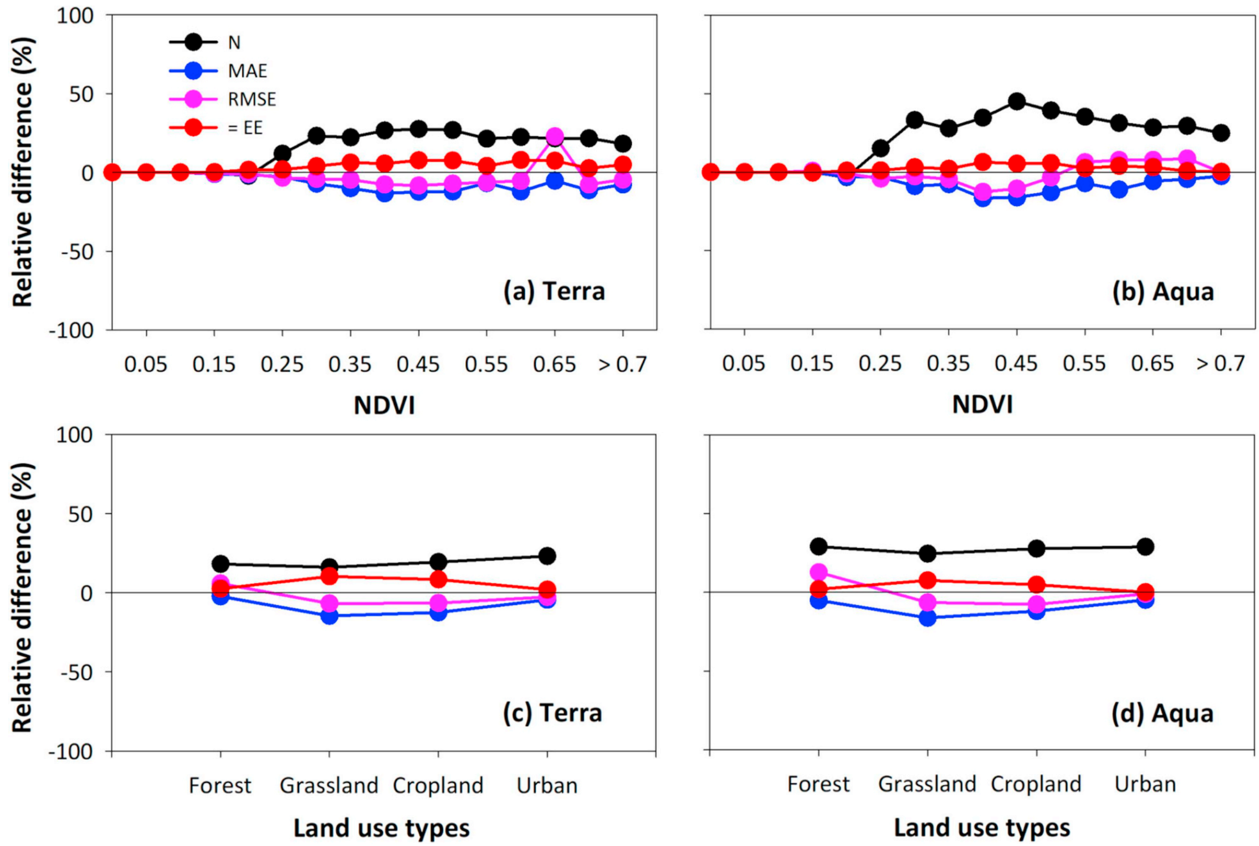

Fig. 10. Relative differences (%) between DTB0 and DTB1 AOD products against AERONET AOD retrievals as a function of (a, b) NDVI and (c, d) land use type for Terra (left panels) and Aqua (right panels) over land.

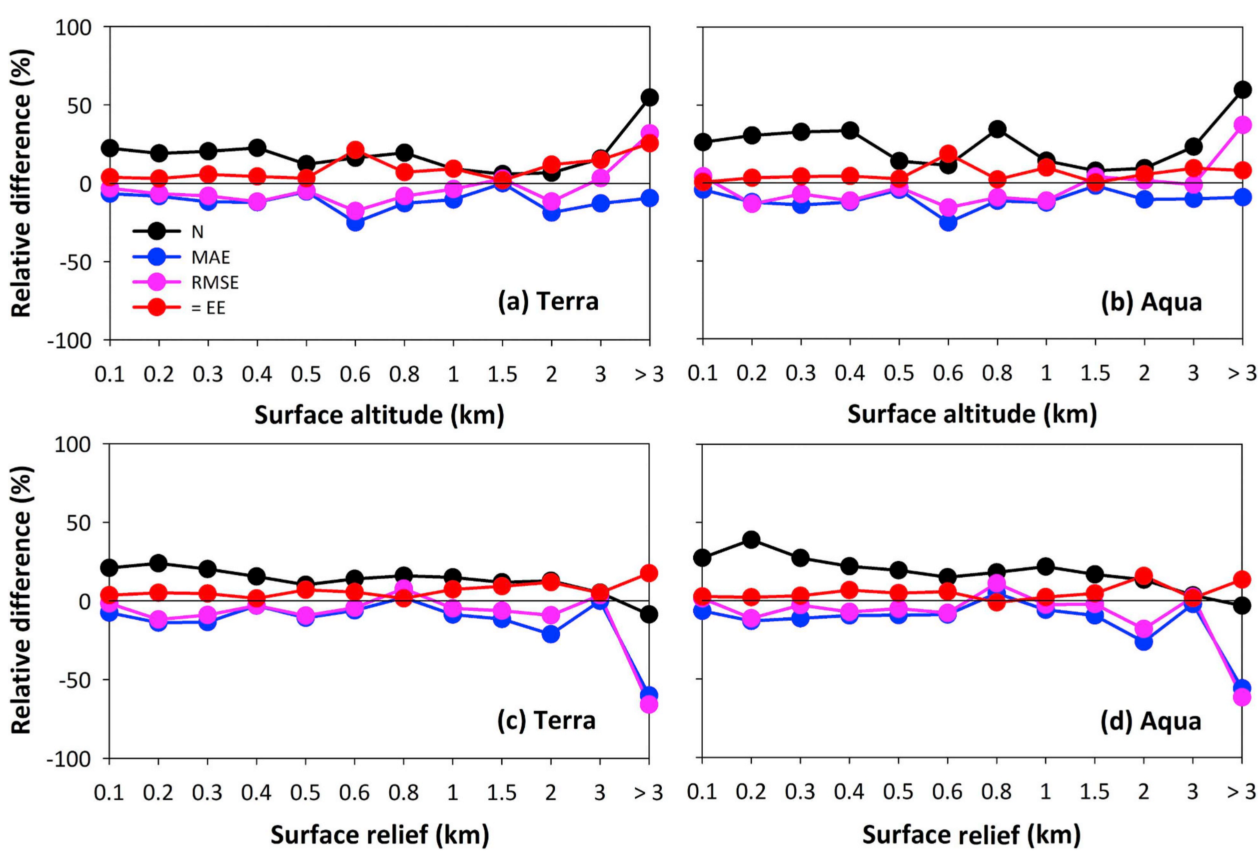

Fig. 11. Same as Fig. 10 but for (a, b) surface altitude and (c, d) surface relief.

Comparisons between operational merged DTB0 and new merged DTB (DTB1) products are done at site, continental, and global scales, as well as for varying surface types, surface altitudes, and surface reliefs. Validations are done against AERONET Version 3 Level 2.0 AOD measurements at 286 sites over land. The number of data samples and the data quality (i.e., percentage of data samples falling within the EE envelope, the MAE, and the RMSE) for DTB1 products are improved at most sites and over all continents. On the global scale, the DTB1 products perform better than the DTB0 products with 17–24% increases in data counts and improved evaluation metrics. The data coverage has also significantly increased, and the data quality improved over varying surface types, altitudes, and reliefs. These results suggest that the new and improved merge approach is more robust and accurate than the current merge approach and can be used operationally to create higher-quality global merged products. This new merge approach will also be useful for related aerosol studies, e.g., aerosol trend analysis and $PM_{2.5}$ prediction.

Declaration of Interest

Z. Li designed the research. J. Wei carried out the research and wrote the initial draft. L. Sun, Y. Peng and L. Wang helped with the refinement of this manuscript. All authors contributed to the interpretation of the results. We declare no conflict of interest.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (91544217), the National Key R&D Program of China (2017YFC1501702), the US National Science Foundation (AGS1534670, AGS1837811), and the BNU Interdisciplinary Research Foundation for the First-Year Doctoral Candidates (BNUXKJC1808). The MODIS products used in this study are available from the Level 1 and Atmosphere Archive and Distribution System (http://ladsweb.nascom.nasa.gov), and AERONET data is available at https://aeronet.gsfc.nasa. Here I want to thank my wife for her hard work and welcome my son to the world.

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