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New customized methods for improvement of the MODIS C6 Dark Target and Deep Blue merged aerosol product

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ABSTRACT

The Moderate resolution and Imaging Spectroradiometer (MODIS) level 2 operational aerosol products (MOD04/MYD04), based on the Dark Target (DT) and the enhanced Deep Blue (DB) algorithms, have been providing daily global aerosol information. The MOD04/MYD04 has different data coverage for the DT and the DB algorithms due to differences in their retrieval methods. Recently in the collection 6 (C6), a DT and DB merged (DTB_{C6}) AOD product has been introduced based on different thresholds of the Normalized Difference Vegetation Index (NDVI) to improve the data coverage. The main objective of this study is to increase the data coverage and reduce the error in the merged DTB_{C6} AOD product by introducing three new customized methods (DTB_{MX}): (i) DTB_{M1}: "use an average of the DT and DB AOD retrievals or the available one for all the NDVI values ", as it is independent of the NDVI values, (ii) DTB_{M2}: "use an average of the DT and DB AOD retrievals or the available one for NDVI ≥ 0.2, and use the DB retrievals for NDVI < 0.2", and (iii) DTB_{M3}: "use AOD retrievals from the DB algorithm for NDVI > 0.3, and use an average of the DT and DB retrievals or the available one for NDVI ≤ 0.3". Validation of the DTB_{MX} is conducted at a global scale from 2004 to 2014 using AERONET AOD measurements from 68 sites located in Asia (9), Europe (22), Southern Africa (8), and North (23) and South America (8), and for comparison purpose, the DTB_{C6} is evaluated for the same period. Results showed that the number of coincident observations of the DTB_{MX} methods compared to the DTB_{C6} is increased by 31%, 41% 30%, and 108% for Asian, European, Southern African, and North and South American sites, respectively. At global scale, the number of coincident observations are increased for the DTB_{M1}, DTB_{M2}, and DTB_{M3} from 29,088 for DTB_{C6}, to 45,937, 45,028, 37,393 which are 58%, 57%, and 29%, respectively more than the for DTB_{C6} observations. For an equal number of coincident observations, the percentage of retrievals within the EE is increased by between 17% to 20% and the RMSE is decreased by up to 15% for the DTB_{MX} methods, but R is the same as for the DTB_{C6}. The percentage above the EE is also decreased by between 43% to 55% due to greater contribution of the DB retrievals. Overall, the performance of all the DTB_{MX} methods is much better than the DTB_{C6}, but the DTB_{M1} is the most robust as it is independent of NDVI values, and significantly increases the data coverage. Therefore, it can be used operationally for global merged AOD retrievals.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua platforms generates extensive geophysical data sets for 36 spectral wavelengths from 0.4 to 14.4 μm with moderate spatial resolutions of 250 m, 500 m, and 1000 m, and good temporal resolution of 1 to 2 days. MODIS' traditional algorithms provide daily observations of mid-visible aerosol optical depth (AOD) at global scale over dark (Kaufman et al., 1997; Levy et al., 2013; Levy et al., 2007) and bright (Hsu et al., 2013; Hsu et al., 2004, 2006) land and ocean surfaces (Levy et al., 2013; Tanré et al., 1997). The latest collection 6 (C6) level 2 MODIS operational aerosol products for Terra (MOD04) and Aqua (MYD04) contain AOD data generated by the Dark Target (DT) land algorithm, the DT ocean algorithm (Levy et al., 2013), and the enhanced Deep Blue (DB) algorithm (Hsu et al., 2013). The MODIS DT algorithm retrieves AOD at 10 km spatial resolution over dark targets, which are selected at 500 m resolution using the top of the atmosphere reflectance (TOA) between 0.01 and 0.25 corrected for gas absorption in the 2.11 μm channel. Then selected pixels are organized into 20 × 20 retrieval boxes (400 pixels) and masked for clouds, snow/ice and other

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bright surfaces as the DT algorithm is unable to retrieve AOD over these surfaces. The 0.66 μm channel is then used for separating land and water pixels, and discarding the 20% darkest and 50% brightest pixels from the retrieval boxes. To perform aerosol retrieval for the highest quality flag (QF = 3), >50 out of 120 pixels (remaining pixels after 70% exclusion from the original 400), and for QF = 2, 1, 0, >30, 20 and 12 pixels are required, respectively. The expected error (EE) over land of the DT algorithm is $\pm(0.05 + 15\%)$ (Levy et al., 2013). 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.

The MODIS DB algorithm retrieves AOD at 10 km spatial resolution over dark, as well as bright urban and desert surfaces using the deep blue channel where these surfaces appear dark. For the DB algorithm, pixels are masked and screened for clouds and snow/ice surfaces, and the remaining pixels are used for calculation of surface reflectance for the 0.412, 0.47 and 0.65 μm channels using (i) the dynamic surface reflectance approach or (ii) a precalculated surface reflectance database or (iii) a combination of these two approaches. The selection of one of these approaches depends on the TOA reflectance in the 2.1 μm channel and the normalized difference vegetation index (NDVI). The DB algorithm first retrieves AOD at 1 km resolution and then aggregates to 10 km. The EE for Deep Blue is dependent on the geometry but is approximately 0.03 + 20% on average (i.e. the algorithms have different error characteristics). In this study, the EE for DT algorithm is used for all calculations.

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 DT and DB have different cloud mask algorithms and evidence has shown that DB reports aerosol above cloud as cloudy free scenes over heavily polluted region and DT tends to over–mask optically thick aerosol plumes (Shi et al., 2015). In C6, the new DT and DB merged (DTB) AOD product consists of the scientific data set "AOD 550 Dark Target–Deep Blue Combined". The purpose of this new product is to improve data coverage over land (Levy et al., 2013; Sayer et al., 2014), 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 (Levy et al., 2013), 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 (Hsu et al., 2013; Sayer et al., 2013). The DTB operational AOD product is accomplished by following thresholds based on climatological NDVI data (Levy et al., 2013): (i) If NDVI > 0.3 then use the DT AOD retrievals, (ii) If NDVI < 0.2 then use the DB AOD retrievals, and (iii) If 0.2 ≤ NDVI ≤ 0.3 then use average of the DT and DB AOD retrievals or the available one with highest quality flag (DT: QF = 3; DB: QF ≥ 2). Based on previous knowledge, i.e., the DT overestimates and the DB underestimates over most sites, the present study introduces new customized methods to improve spatio–temporal coverage and reduce the error in the DTB_{C6} AOD product, and compares the results with the DTB_{C6} AOD product from 2004 to 2014.

2. Dataset

In this study, Terra–MODIS C6 level 2 operational aerosol product (MOD04) at 10 km spatial resolution was downloaded from "the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC)" (https://ladsweb.nascom.nasa.gov/) to obtain the DT, the DB, and the DTB AOD retrievals for evaluation. The Terra–MODIS monthly level 3 Normalized Difference Vegetation Index (NDVI) product (MOD13A3) was downloaded to obtain the parameter "1 km NDVI" to incorporate into the new customized methods. For evaluation of AOD retrievals, Aerosol Robotic Network (AERONET) (Holben et al., 1998; Holben et al., 2001) Level 2.0 Version 2 (cloud–screened and quality–assured) (Smirnov et al., 2000) AOD data were downloaded from http://aeronet.gsfc.nasa.gov for all sites and the relevant time periods. Table 1 gives a detailed summary of the dataset.

3. Methods

In this study, three new customized methods (DTB_{MX}, where x = 1, 2, or 3) dependent or independent of the NDVI values are introduced to improve spatio-temporal coverage and reduce the error in the DTB_{C6} AOD product. These DTB_{MX} are validated using AERONET Level 2.0 Version 2 AOD measurements at 550 nm from 2004 to 2014 over 68 sites located in Asia (9), Southern Africa (6), Europe (22), and North (23) and South (8) America, and compared with DTB_{C6} AOD retrievals. As AERONET does not make AOD measurements at 550 nm, AOD is interpolated to 550 nm using standard Ångström exponent (α) (Sayer et al., 2013). For this, only those DT and DB AOD retrievals at 550 nm passing recommended quality assurance (AQ) checks (Hsu et al., 2013; Levy et al., 2013; Sayer et al., 2013) are used (for DT, corresponding to retrievals flagged QA = 3; for DB, retrievals flagged QA = 2 or QA = 3). The DT and DB retrievals are obtained from the Scientific Data Set (SDS) "Optical Depth Land and Ocean" and "Deep Blue Aerosol Optical Depth 550 Land Best Estimate", respectively. For comparison purpose, the DTB_{C6} AOD retrievals are obtained from the SDS "AOD 550 Dark Target Deep Blue Combined" and filtered for flagged QA = 3 using the SDS "AOD 550 Dark Target Deep Blue Combined QA Flag".

Method–1 (DTB_{M1}) "use average of the DT and DB AOD retrievals or the available one for all the NDVI values is introduced, which is independent of the NDVI values. Method–2 (DTB_{M2})" "use an average of the DT and DB AOD retrievals or the available one for NDVI ≥ 0.2, and use the DB retrievals for NDVI < 0.2" is introduced to improve the retrievals and reduce the error when the DT algorithm tends to overestimate for NDVI > 0.3. Method–3 (DTB_{M3}) "use AOD retrievals from the DB algorithm for NDVI > 0.3, and use average of the DT and DB retrievals or the available one for NDVI ≤ 0.3" is introduced, because sometimes the DB algorithm performs better than the DT algorithm over surfaces where NDVI > 0.3. Therefore, this average of DT and DB can address the tendency of the DT and DB algorithms to show opposite, i.e., under– or over–estimation of surface reflectance. As the DTB_{M2} and DTB_{M3} retrievals are based on NDVI values, monthly NDVI maps (Fig. 1) are generated for all sites using the MODIS level 3 monthly NDVI product (MOD13A3). Most of the sites are dominated by vegetated surfaces in spring and summer (NDVI > 0.3) and non-vegetated surfaces in autumn and winter (NDVI < 0.2).

To increase the number of statistical samples for validation, collocations are defined as the average of at least two AERONET AOD measurements between 10:00 and 12:00 local time and at least two pixels of MODIS AOD observations within a sampling window of 3 × 3 pixels (average of 9 pixels) centered on the AERONET site, i.e., average within a 30 km × 30 km region. The errors of the retrievals are reported using root mean square error (RMSE, Eq. (1)), and the expected error (EE, Eq. (2)) of the DT algorithm over land. The percent relative difference in a number of coincident observations, the EE, RMSE, and R is calculated using Eq. (3).

4. Results and discussion

4.1. Validation of the customized methods at local scale

The performance of the merged DTB_{C6} and DTB_{MX} (where x = 1, 2 or 3) methods at each AERONET site was evaluated based on (a) highest data count, (b) highest percentage within the EE, (c) lowest RMSE, and (d) highest correlation coefficient (Fig. 2). To evaluate the performance of the DTB_{C6} and DTB_{MX} at local scale (individual site), the following criteria are defined: if relative difference/error using Eq. (3) is (i) 20% for the coincident observations, (ii) 10% for the percentage of retrievals within the EE, (iii) 10% for the correlation coefficient, and (iv) 5% for the RMSE, then the DTB_{C6} and DTB_{MX} are considered to perform

Table 1
Summary of the dataset used in the current study at global scale from 2004 to 2014.

Data	Scientific Data Set (SDS) name	Contents
MOD04	Optical_Depth_Land_And_Ocean	DT over land and ocean
	Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate	DB over land
	AOD_550_Dark_Target_Deep_Blue_Combined	DB, DT, or their average
	AOD_550_Dark_Target_Deep_Blue_Combined_QA_Flag	Indicates quality of pixel
MOD13A3	1 km NDVI	Monthly NDVI
AERONET		AOD

equally well performed over that site, and these sites are denoted by a "plus" symbol. In Fig. 2, "triangle" and "circle" symbols represent that the DTB_{C6}, and the DTB_{MX} respectively performed better over the individual sites, and color variations represent the magnitude of the relative difference error (%) between the DTB_{C6} and DTB_{MX}. As no method, can perform well for all sites, the method is considered robust if it can perform better for most of the sites.

For the data counts, 11 out of 68 sites have data counts within 20% of both algorithms, and the remaining 57 sites have data counts larger by 21% to >100% for the DTB_{M1} (Fig. 2(a-i)) and DTB_{M2} (Fig. 2(a-ii)) methods, compared to the DTB_{C6}. This indicates that DTB_{M1} and DTB_{M2} significantly improved the spatial-temporal coverage at local scale. The performance of the DTB_{M3} method (Fig. 2(a-iii)) was not as good as DTB_{M1} or DTB_{M2}, which may be due to the limitation of the

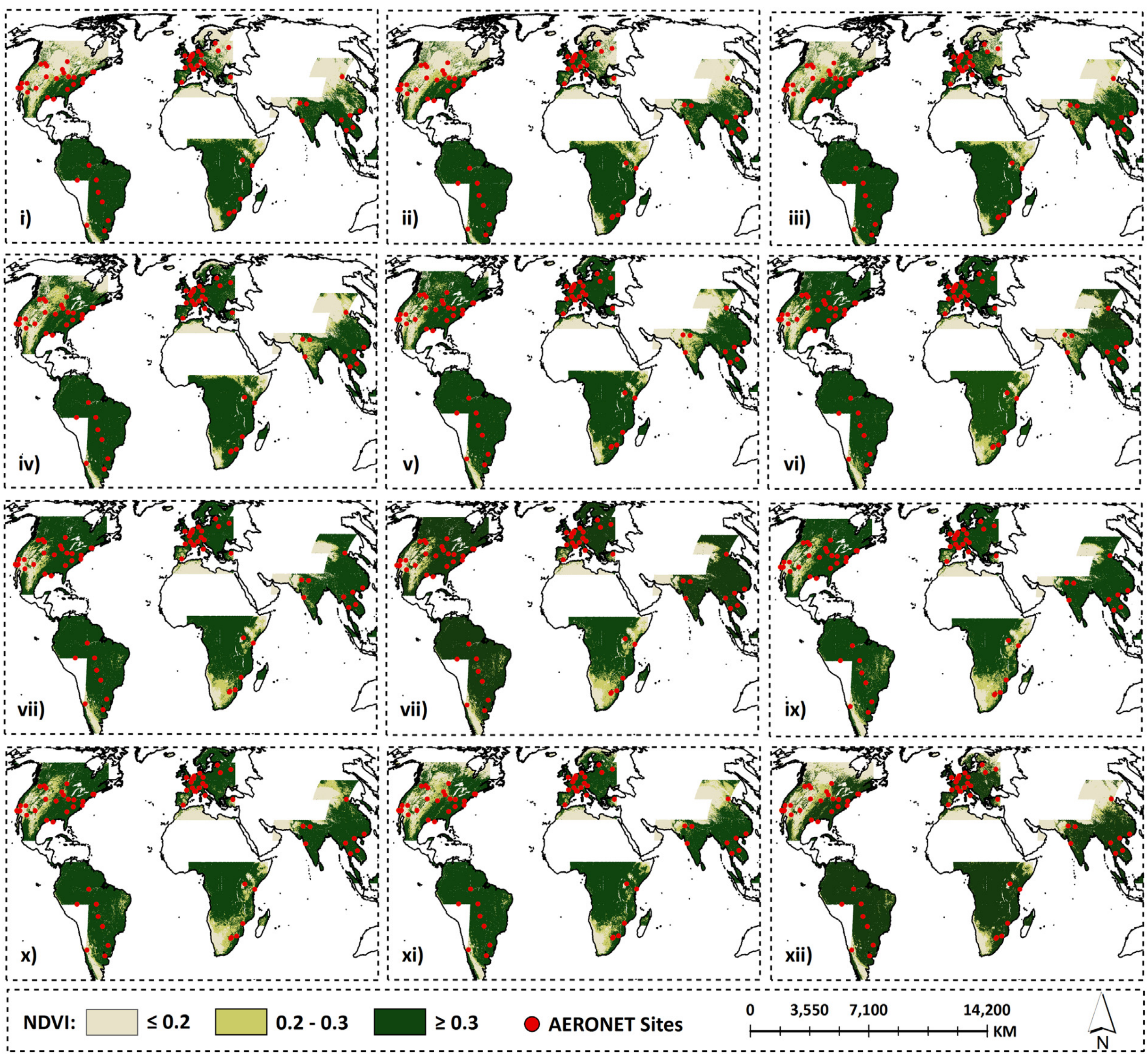

Fig. 1. Monthly NDVI maps for (i) January, (ii) February, (iii) March, (iv) April, (v) May, (vi) June, (vii) July, (viii) August, (ix) September, (x) October, (xi) November, and (xii) December.

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

$$EE = \pm(0.05 + 15\%)$$

$$\%Relative\ difference = \left(\frac{DTB_{C6} - DTB_{Mx}}{DTB_{C6}}\right) \times 100$$

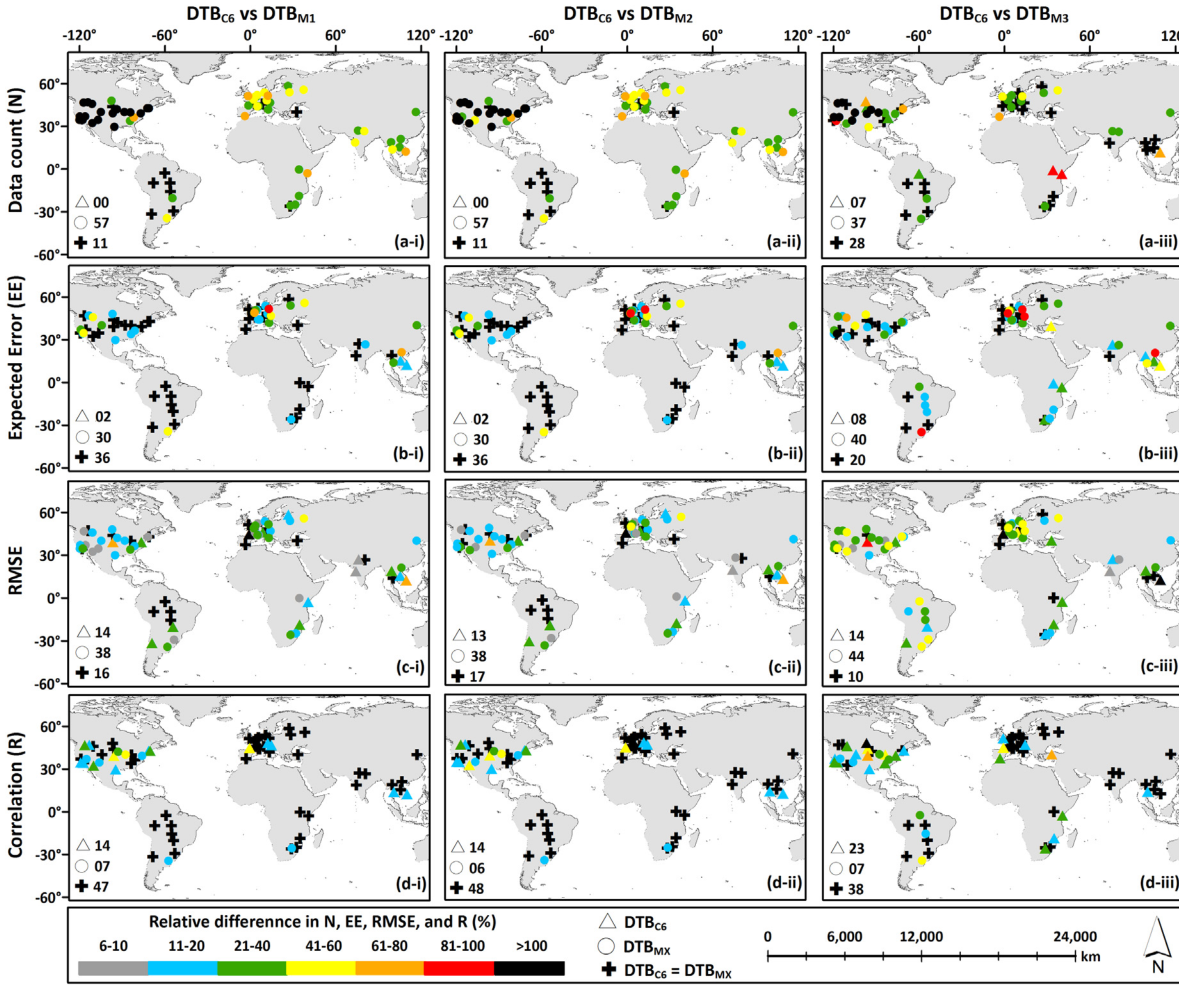

Fig. 2. Maps showing the best performing method based on different statics: (a) the data count, (b) fraction within the EE, (c) RMSE, and (d) correlation coefficient. Where (i) = DTB_{M1}, (ii) = DTB_{M2} and (iii) = DTB_{M3}.

DB algorithm as the DTB_{M3} has greater contribution from the DB algorithm. However, DTB_{M3} performed better than DTB_{C6}, and data counts increased by between 21% and >100% for 37 individual sites. Overall, significant improvement is observed in the data counts using the DTB_{MX} methods especially over North America where data counts increased by up to >100% compared to the DTB_{C6}.

For the percentage of retrievals within the EE, the DTB_{M1} (Fig. 2(b-i)) and DTB_{M2} (Fig. 2(b-ii)) methods performed equally at individual sites, as 30 out of 68 sites show great improvement and the percentage within the EE is increased by 11 to 100% compared to the DTB_{C6}. There are 36 sites where the DTB_{C6}, and the DTB_{M1} and DTB_{M2} methods obtained 10% within the EE, and these three methods performed equally over these sites. The DTB_{C6} performed well at only two Asian sites where the percentage of the EE increased by up to 20%. The DTB_{M3} (Fig. 2(b-iii)) performed better than the DTB_{M1} and DTB_{M2} methods due to greater contribution from the DB retrievals. The number of sites where the DTB_{C6} and DTB_{M3} performed well and equally to each other are 8, 40, and 20, respectively. Overall, the DTB_{MX} methods are significantly improved, i.e. relative difference increased by up to 100% of the percentage within the EE at global scale compared to the DTB_{C6}.

The DTB_{MX} methods also significantly reduced the RMSE at global scale, and the DTB_{M1} (Fig. 2(c-i)) and DTB_{M2} (Fig. 2(C-ii)) methods performed equally at over 38 sites. The RMSE reduced by up to 80% for European sites, while the DTB_{M3} (Fig. 2(b-iii)) performed better than the DTB_{M1} and DTB_{M2} methods, and significantly reduced the error for European, and North and South American sites. The DTB_{MX} methods performed better than the DTB_{C6} between 38 and 44 sites and reduced the error, and 10 to 17 sites where they performed equally, i.e., the relative difference is within 5%.

The DTB_{C6} and DTB_{MX} performed equally between 38 and 48 sites, as R is within 10% (Fig. 2d), and the DTB_{C6} performed better between 14 and 23 sites. The maximum difference in correlation is observed by up to 60%, and 80% over European and North American sites respectively when DTB_{C6} is compared to the DTB_{M1} and DTB_{M2}, and DTB_{M3}. This may be due to great differences in the number of coincident observations between DTB_{C6} and DTB_{MX} as shown in Fig. 2a. The DTB_{MX} also have a high correlation with an improvement of up to 60% over the same region.

Overall, these results suggest that the DTB_{MX} methods are more efficient and performed better at local scale than the merged DTB_{C6} method with lower RMSE, many more data counts and larger percentage within the EE.

4.2. Validation of the customized methods at regional scale

To evaluate performance of the DTB_{C6} and DTB_{MX} at regional scale, the following criteria are defined: if relative difference/error using Eq. (3) is (i) 10% for the coincident observations, (ii) 10% for the percentage of retrievals within the EE, (iii) 10% for the correlation coefficient, and

(iv) 5% for the RMSE, then the DTB_{C6} and DTB_{MX} are considered to perform equally well over these sites.

4.2.1. Validation over Asian sites

The DTB_{MX} methods were validated over nine sites located in Asia and compared with the DTB_{C6} AOD retrievals (Fig. 3) to find the best method with respect to high spatio-temporal coverage and low error. In Fig. 3, coincident observations shown as orange, blue and black colors represent "above", "within" and "below" the EE, black solid line = 1:1 line, and dashed lines = EE envelope. Results show significant improvement in spatio-temporal coverage as the number of coincident observations of the DTB_{M1}, DTB_{M2}, and DTB_{M3} increased by 31%, 30%, and 16% respectively, compared to the DTB_{C6} (Fig. 3). This is because these methods consider an average of DT and DB or the available one, for a large range of NDVI values, while DTB_{C6} considers only for a small range of NDVI values (Sayer et al., 2014). Also, five out of the nine Asian sites have NDVI ≥ 0.3 throughout the year, and DTB_{C6} only considers DT retrievals for these sites, while DTB_{M1} and DT_{M2} consider both DT and DB retrievals, which increases the coverage of the dataset. The advantage of using the average of both DT and DB retrievals is to minimize under– and over–estimation of AOD in the DTB_{C6}. The DTB_{M3} has fewer observations than the DTB_{M1} and DTB_{M2} due to a greater contribution of the DB algorithm as DB has fewer retrievals than DT over these sites. All the methods including the DTB_{C6} have the same RMSE and correlation coefficient which is within 5%.

These results might be statistically insignificant, as the number of coincident observations are not equal. Therefore, to discuss statistical significance of the comparison with DTB_{C6}, an equal number of statistical samples is selected (Table 2). Results show that the percentage of the retrievals within the EE for the DTB_{MX} is increased by 11% to 15%, and the percentage above the EE is decreased up to 29% compared to the DTB_{C6}. The RMSE is decreased by between 14% and 16%, and R remains within 5%. Overall, the DTB_{M1} and DTB_{M2} performed equally over the Asian sites, and significantly increased the spatio-temporal coverage while preserving the quality of AOD retrievals (Table 2).

Table 2
Statistical summary of the DTB_{C6}, DTB_{M1}, DTB_{M2}, and DTB_{M3} AOD retrievals over Asian sites from 2004 to 2014.

Region: Asia				
AERONET Sites: Beijing, Jaipur, Kanpur, Pune, Chiang Mai met sta., NGHIA do, NhaTrang, Silpakorn uni., and Ubon Ratchathani				
Statistical parameters	DTB_{C6}	DTB_{M1}	DTB_{M2}	DTB_{M3}
Coincident observations (N)	4588	4588	4588	4588
Correlation coefficient (R)	0.88	0.90	0.90	0.89
RMSE	0.21	0.17	0.17	0.18
% within EE	56.91	65.26	65.19	63.21
% above EE	33.44	23.69	23.71	23.10
% below EE	09.65	11.05	11.09	13.69

4.2.2. Validation over Southern African sites

Aerosol concentrations over Southern African sites are half of the those observed over Asian sites (Fig. 4), indicating better air quality over Southern Africa. Fig. 4 shows significant improvements up to 30% in coincident observations for the DTB_{M1}, and DTB_{M2} methods, compared to the DTB_{C6} observations over the six Southern African sites. However, the number of coincident observations of the DTB_{M3} are 13%

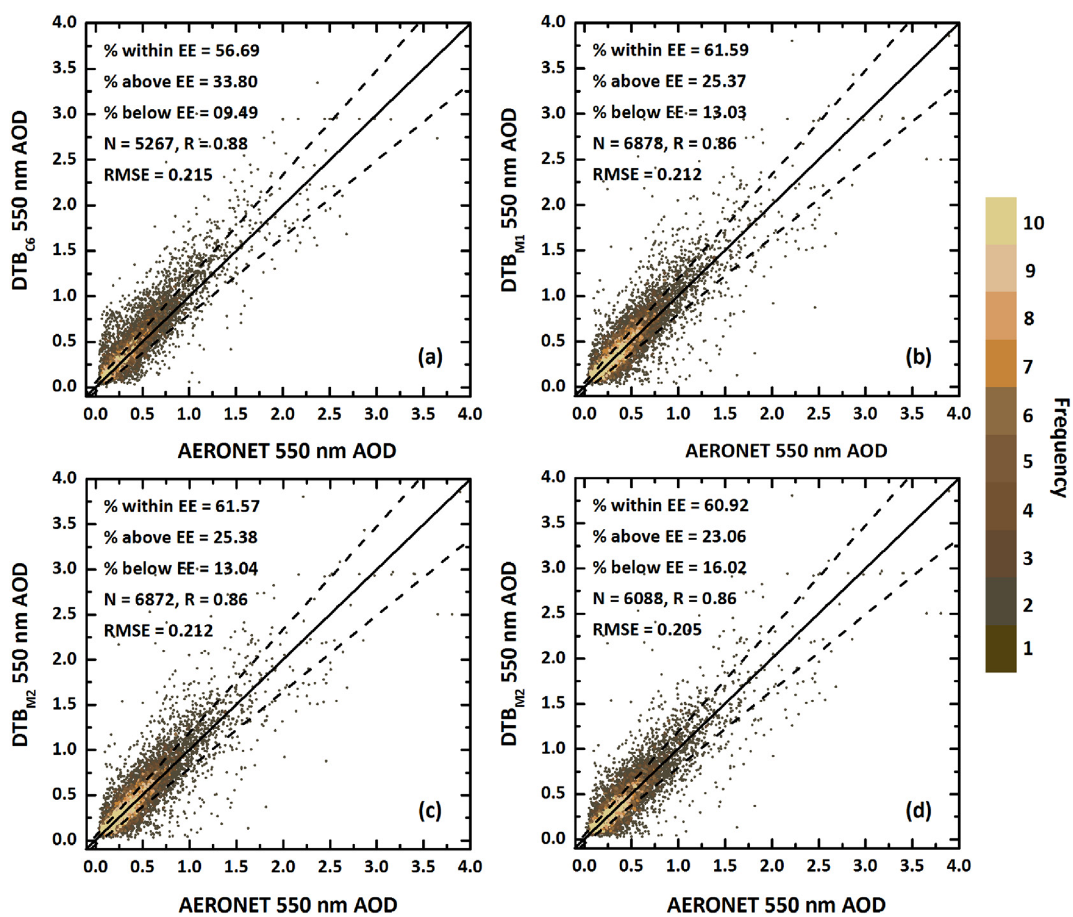

Fig. 3. Validation of the (a) DTB_{C6}, (b) DTB_{M1}, (c) DTB_{M2}, (d) DTB_{M3} over Asian sites from 2004 to 2014. Whereas, solid black line = 1:1 line, and dashed lines = EE envelope.

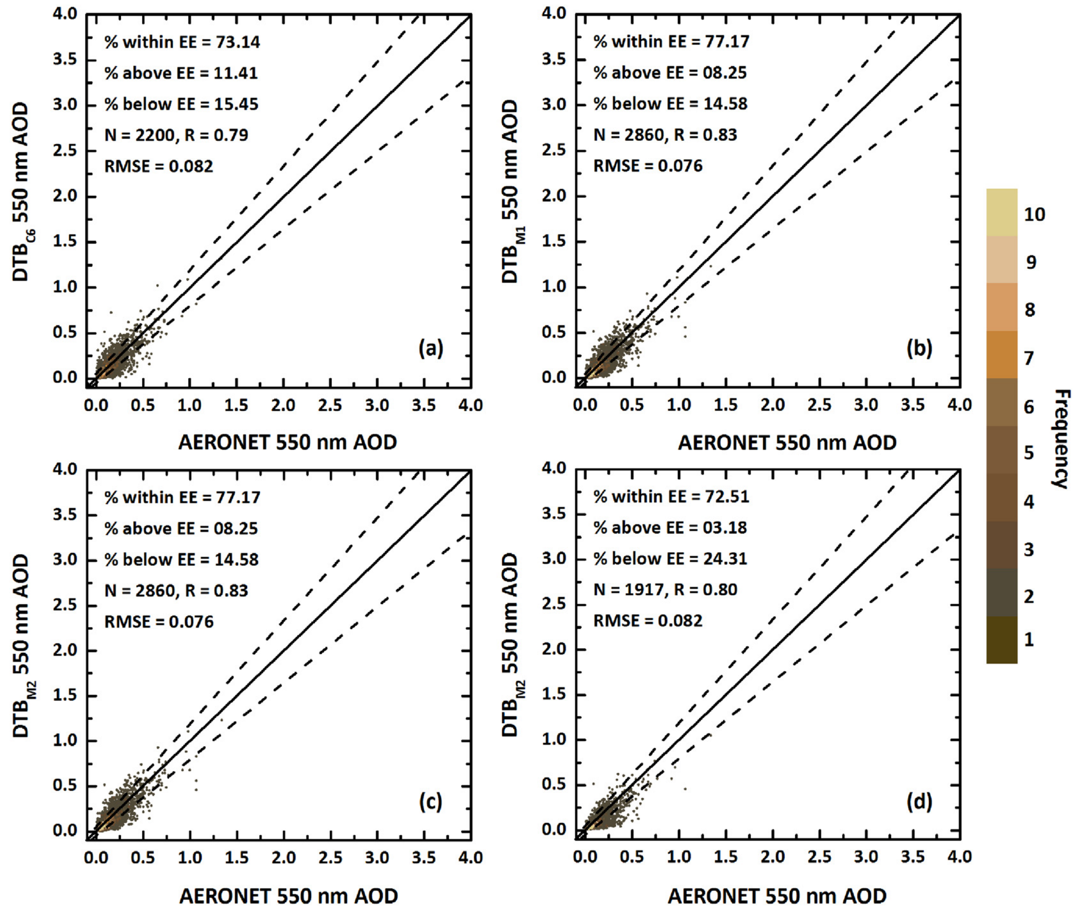

Fig. 4. Validation of the (a) DTB_{C6}, (b) DTB_{M1}, (c) DTB_{M2}, (d) DTB_{M3} over Southern African sites from 2004 to 2014. Whereas, solid black line = 1:1 line, and dashed lines = EE envelope.

fewer than the DTB_{C6} observations, as almost all sites have NDVI ≥ 0.3, and DB always has fewer retrievals than DT over dark vegetated surfaces. The RMSE is decreased by up to 7%, and R and the percentage of retrievals within the EE are within 10% for DTB_{M1}, and DTB_{M2}, while DTB_{M3} has similar statistics to the DTB_{C6}.

For statistical significance, an equal number of retrievals are selected for all the methods and validated against AERONET AOD measurements (Table 3). Significant improvements are observed for DTB_{M1}, and DTB_{M2} for all statistical metrics, i.e., RMSE is decreased by 15%, and R and the percentage of retrievals within the EE are within 10% (Table 3). However, results are not satisfactory for the DTB_{M3} due to greater contribution of the DB retrievals which increased the RMSE and decreased the percentage of retrievals within the EE. These results suggest that DTB_{M1} and DTB_{M2} are robust and much better than the DTB_{C6} over Southern African sites.

Table 3
Statistical summary of the DTB_{C6}, DTB_{M1}, DTB_{M2}, and DTB_{M3} AOD retrievals over Southern African sites from 2004 to 2014.

Region: Southern Africa				
AERONET Sites: CRPSM Malindi, Gorongosa, ICIPE mbita, Pretoria CSIR, Skukuza, and Wits university.				
Statistical parameters	DTB_{C6}	DTB_{M1}	DTB_{M2}	DTB_{M3}
Coincident observations (N)	1494	1494	1494	1494
Correlation coefficient (R)	0.77	0.85	0.85	0.80
RMSE	0.080	0.068	0.068	0.082
% within EE	75.10	81.53	81.53	72.82
% above EE	09.64	03.68	03.68	03.81
% below EE	15.26	14.79	14.79	24.37

4.2.3. Validation over European sites

Air quality conditions over the European sites, like the Southern African sites, are much better than the Asian sites, with most of the AOD observations below 1.0, which is almost three times lower than observed over Asia. Fig. 5 shows significant improvements for all the DTB_{MX} for the number of coincident observations, the percentage within the EE, and the RMSE, while R is within 5%. For the DTB_{M1}, DTB_{M2} and DTB_{M3}, the number of coincident observations increased by 41%, 41% and 25%, the percentage of retrievals within the EE increased by 18%, 18%, 19%, and the RMSE decreased by 14%, 14%, and 16%, respectively. The small RMSE for DTB_{M3} is due to the greater contribution of the DB retrievals, which indicates that DB performs better than DT over European sites.

When an equal number of coincident observations are selected (Table 4), results are significantly improved for DTB_{M1}, and DTB_{M2}, whereas the DTB_{M3} has comparable statistics with the DTB_{C6}. For the DTB_{M1}, and DTB_{M2}, the percentage of retrievals within the EE increased by 24%, and RMSE decreased by 28%, while R is within 5%. These results are similar to those observed for Asian and Southern African sites, i.e., the DTB_{M1} and DTB_{M2} had significantly improved data coverage, and the errors in the DTB_{C6} were reduced.

4.2.4. Validation over North and South American sites

North and South American AOD observations are similar to those of Southern Africa (Fig. 3) and Europe (Fig. 4) has values below 1.0 for most days (Fig. 6), which indicates good air quality conditions. However, the performance of the DTB_{C6} is much inferior to Southern African and European sites, as the RMSE is large, and the percentage of retrievals within the EE and R are low. The percentage of retrievals above/within/below the EE is almost the same as observed over Asia (Fig. 2). However,

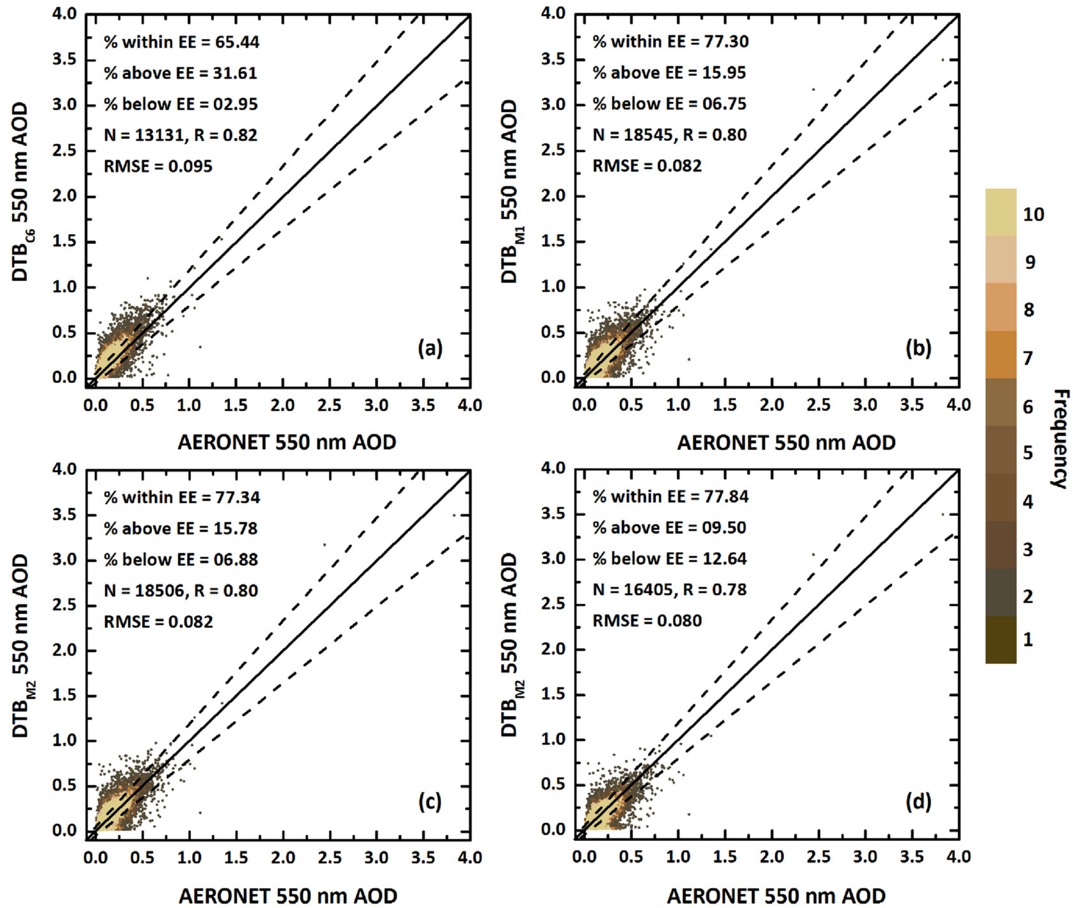

Fig. 5. Validation of the (a) DTB_{C6}, (b) DTB_{M1}, (c) DTB_{M2}, (d) DTB_{M3} over European sites from 2004 to 2014. Whereas, solid black line = 1:1 line, and dashed lines = EE envelope.

better correlation is observed between DTB_{C6} and AERONET AOD over Asian sites, which indicates that the DT and DB algorithms follow the trend of the local air pollution and represent actual air quality conditions over the region.

The DT and DB are well correlated with each other over North and South America (Sayer et al., 2014) but they are less correlated with AERONET measurements as observed in this study. Fig. 6 shows that the number of coincident observations for all the DTB_{MX} increased by 50% to 108%, the percentage of retrievals within the EE increased by 9% to 21%, and the RMSE decreased by 8% to 22%, whereas R is within 10%. For DTB_{M3}, the large percentage of retrievals within the EE and the small RMSE indicate that the most of the DB retrievals are close to the AERONET AOD measurements, but these retrievals also give fewer coincident observations.

For an equal number of coincident observations (Table 5), the percentage of retrievals for the DTB_{MX} increased by 11% to 19%, the RMSE decreased by 7% to 12%, and R is within 10%. The performance of the DTB_{M3} is slightly better than the DTB_{M1} and DTB_{M2} due to greater contribution from the DB algorithm, as the DB retrievals are more similar to the AERONET AOD measurements over the region. Overall, the performance of the DTB_{Mx} is much better than DTB_{C6} as it increases the data coverage while improving the quality of AOD retrievals.

4.3. Validation of the customized methods at global scale

To evaluate the performance of the DTB_{C6} and DTB_{MX} at global scale, the same criteria are used as defined for regional scale. For implementation of the DTB_{MX} methods at global scale, validation was conducted over 68 AERONET sites located in Asia (9), Southern Africa (6), Europe (22), and North (23) and South (8) America, using AERONET level 2.0 measurements from 2004 to 2014 (Fig. 7). Results show that the number of coincident observations increased from 29,088 (Fig. 7a) to 45,937 for the DTB_{M1} (Fig. 7b), to 45,028 for the DTB_{M2} (Fig. 7c), and to 37,393 for the DTB_{M3} (Fig. 5g) which are 58%, 57%, and 29%,

Table 4
Statistical summary of the DTB_{C6}, DTB_{M1}, DTB_{M2}, and DTB_{M3} AOD retrievals over European sites from 2004 to 2014.

Region: Europe

AERONET Sites: Arcachon, Aubiere lamp, Avignon, Brussels, Cabauw, Carpentras, Chilbolton, Granada, Hamburg, Ispra lighthouse, Kanzelhohe obs. lighthouse, Leipzig, Lille, Minsk, Moscow msu mo, Munich university, OHP observatoire, Palaiseau, Paris, Rome Tor Vergata, Toravere, and Tubitak uzay ankara.

Statistical parameters	DTB_{C6}	DTB_{M1}	DTB_{M2}	DTB_{M3}
Coincident observations (N)	11,537	11,537	11,537	11,537
Correlation coefficient (R)	0.82	0.84	0.84	0.79
RMSE	0.092	0.066	0.066	0.073
% within EE	66.30	82.33	82.37	67.18
% above EE	30.79	12.13	11.90	12.56
% below EE	02.91	05.54	05.73	20.32

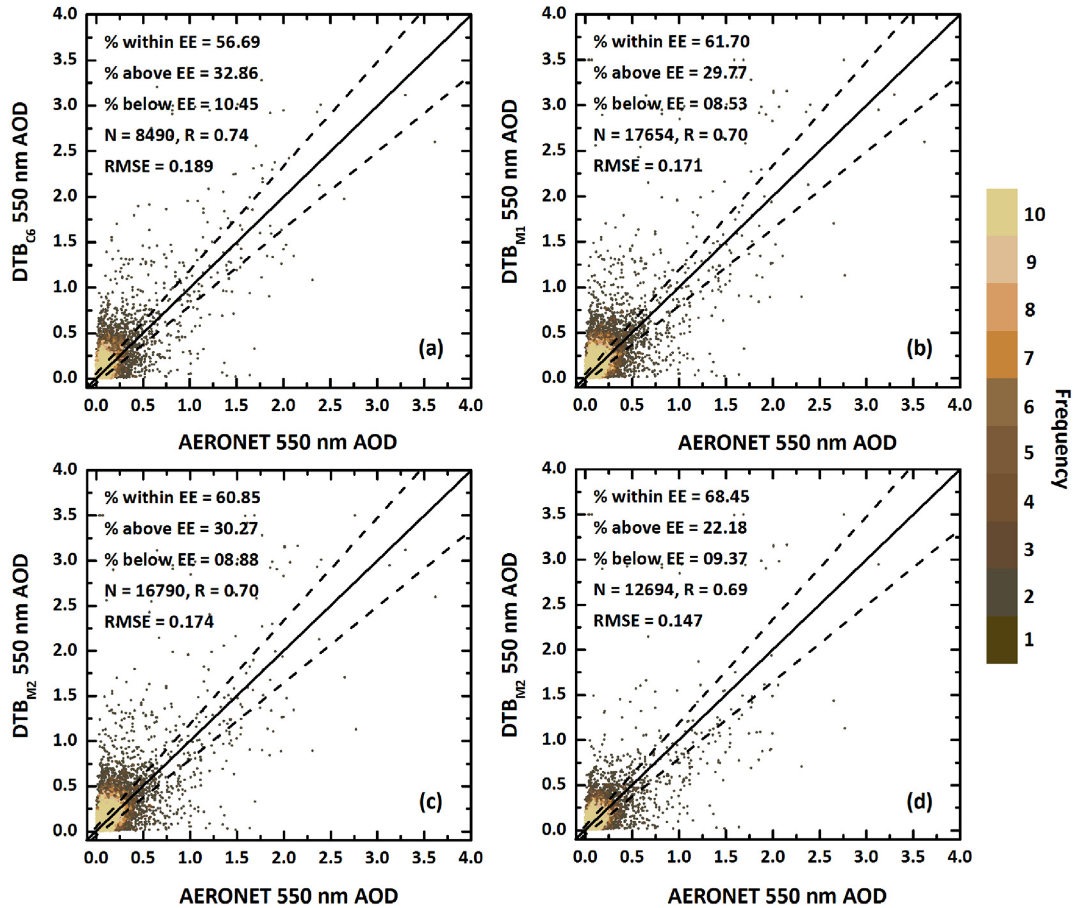

Fig. 6. Validation of the (a) DTB_{C6}, (b) DTB_{M1}, (c) DTB_{M2}, (d) DTB_{M3} over North and South American sites from 2004 to 2014. Whereas, solid black line = 1:1 line, and dashed lines = EE envelope.

respectively, greater than the DTB_{C6} observations. The percentage within the EE increased by 11% to 15%, whereas R and RMSE are within 5%. The percentage of retrievals above the EE are reduced by up to 28%, for the DTB_{M1} and DTB_{M2} due to using an average of the DT and DB algorithms for a large range of NDVI values. This is because the DB algorithm helps to reduce the large percentage above the EE of the DT algorithm. Overall, the number of coincident observations and the percentage within the EE are increased, and R and RMSE are within 5% of the DTB_{C6}. These results suggest that the DTB_{MX} methods meet the main objective of the merged DTB_{C6} AOD product i.e. to increase coverage while preserving the quality of AOD retrievals.

For statistical significance at global scale, an equal number of coincident observations are selected (Table 6). Results show significant improvements, i.e., the percentage of retrievals within the EE increased by 17% to 20%, the RMSE decreased by up to 15% for the DTB_{MX} methods, and R is the same as the DTB_{C6}. The percentage above the EE also decreased by 43% to 55% due to more contributions of the DB algorithm, as most of the time, the DB retrievals are less different from the AERONET AOD measurements, than to the DT retrievals. Overall, the performance of the DTB_{MX} methods is much better than the DTB_{C6}, as they increased the percentage within the EE and reduced the error, while having similar correlation to the AERONET AOD as the DTB_{C6}.

5. Summary and conclusion

The main objective of this study is to improve data coverage and reduce the error in the merged DTB_{C6} AOD product. For this, three new customized methods (i) DTB_{M1}: "use an average of the DT and DB AOD retrievals or the available one for all the NDVI values", as it is independent of the NDVI values, (ii) DTB_{M2}: "use an average of the DT and

Table 5
Statistical summary of the DTB_{C6}, DTB_{M1}, DTB_{M2}, and DTB_{M3} AOD retrievals over North and South American sites from 2004 to 2014.

Region: North and South America

AERONET Sites: Ames, Appalachian State, Billerica, Bondville, Bozeman, BSRN Bao Boulder, CalTech, Dayton, Frenchman flat, Fresno, Georgia tech., Grand forks, GSFC, Harvard forest, Konza EDC, Missoula, Rimrock, Sevilleta, Sioux falls, Table Mountain CA., Tucson, UCSB, Univ. of Houston, Alta Floresta, Campo Grande SONDA, CASLEO, CEILAP-BA, CUIABA-MIRANDA, Manaus EMBRAPA, Rio Branco, and Sao Martinho SONDA.

Statistical parameters	DTB_{C6}	DTB_{M1}	DTB_{M2}	DTB_{M3}
Coincident observations (N)	5886	5886	5886	5886
Correlation coefficient (R)	0.74	0.73	0.73	0.71
RMSE	0.170	0.158	0.158	0.150
% within EE	58.17	64.83	65.15	69.41
% above EE	30.45	25.09	24.57	19.98
% below EE	11.38	10.08	10.28	10.61

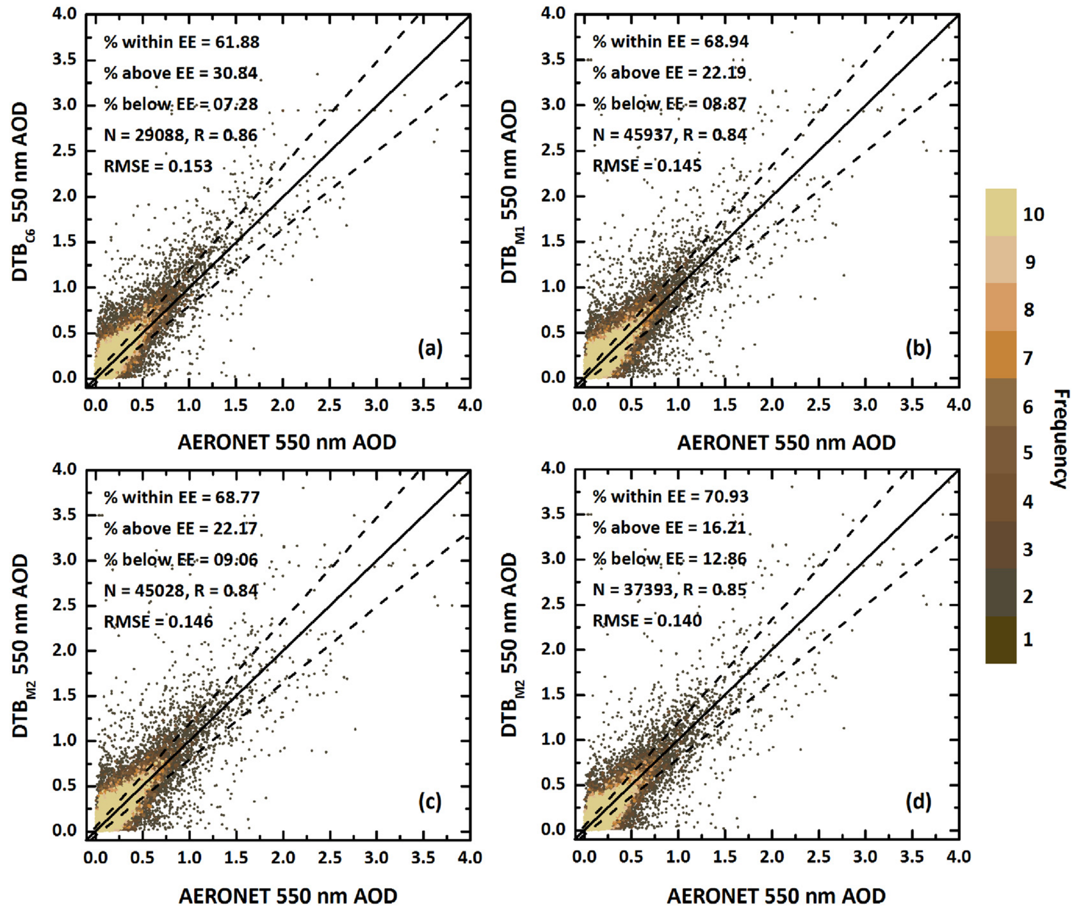

Fig. 7. Global validation of the merge (a) DTB_{C6} (b) DTB_{M1}, (c) DTB_{M2}, and (d) DTB_{M3} observations over 68 sites located in Asia, Europe, Southern Africa, and North and South America using AERONET AOD measurements from 2004 to 2014. Whereas, solid black line = 1:1 line, and dashed lines = EE envelope.

DB AOD retrievals or the available one for NDVI ≥ 0.2, and use the DB retrievals for NDVI < 0.2", and (iii) DTB_{M3}: "use AOD retrievals from the DB algorithm for NDVI > 0.3, and use an average of the DT and DB retrievals or the available one for NDVI ≤ 0.3" are introduced. For this, only those DT and DB AOD retrievals at 550 nm passing recommended quality assurance (AQ) checks are used (for DT, corresponding to retrievals flagged QA = 3; for DB, retrievals flagged QA = 2 or QA = 3). A monthly NDVI map is developed using the MODIS level 3 monthly NDVI (MOD13A3) product to implement the DTB_{M2} and DTB_{M3} methods. Validation is conducted at local, regional and global scales using AERONET AOD measurements from 68 sites located in Asia (9), Europe (22), Southern Africa (8), and North (23) and South America (8).

Results showed that the number of coincident observations and the percentage of retrievals within/above/below the EE are significantly improved for all regions, the RMSE decreased, and R is within 10% error for the DTB_{MX} methods, compared to the DTB_{C6}. The DTB_{MX} methods performed significantly better for all regions, except for the DTB_{M3} which is less reliable over Southern African sites due to greater contribution from the DB algorithm. At global scale, the performance of each DTB_{MX} method is much better than the DTB_{C6}, but the DTB_{M1} is more robust than the DTB_{M2} and DTB_{M3} as (i) it is independent of NDVI, and (ii) significantly increases the number of observations, which meets the main objective of the DTB_{C6}, which is increase the data coverage while preserving the quality of the retrievals. Therefore these results suggest that the DTB_{M1} method, which is independent of NDVI values, can be used operationally for global merged DTB_{C6} AOD retrievals.

The operational DTB product uses simple regional NDVI thresholds for a given region and season. This avoids potential discontinuities in space/time at a given area, which might result from jumping between algorithms. This was done to aid in long-term consistency of the data product for trend calculations (even though this might mean that coverage or absolute error are not optimal). The customized method introduced here increases coverage and decreases error but it may result in changes to the error characteristics of the resulting AOD product over time, as DT, DB, and their average all have different contextual biases. This needs further investigation.

Table 6
Statistical summary of the DTB_{C6}, DTB_{M1}, DTB_{M2}, and DTB_{M3} AOD retrievals over 68 global sites from 2004 to 2014.

Region: Asia, Europe, Southern Africa, and North and South America				
Statistical parameters	DTB_{C6}	DTB_{M1}	DTB_{M2}	DTB_{M3}
Coincident observations (N)	23,505	23,505	23,505	23,505
Correlation coefficient (R)	0.88	0.89	0.89	0.88
RMSE	0.142	0.121	0.121	0.122
% within EE	62.99	74.56	74.65	73.56
% above EE	29.88	17.11	16.86	13.44
% below EE	07.13	08.33	08.49	13.00

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